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OPERATIONAL TEST AND EVALUATION OF AUTOMATED CONSTRUCTION DEVICES

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Reader: ______________________
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ABSTACT

OPERATIONAL TEST AND EVALUATION OF AUTOMATED CONSTRUCTION DEVICES

by

LEE R. CRANMER, CAPT, U.S.A.F.

1990

Master of Science in Architectural Engineering

The University of Texas at Austin

138 Pages

Today we are poised on the verge of an automation revolution in the construction industry. A standard operational test and evaluation plan which will enable systematic and uniform examination of automated construction devices is required. Thus, this study has at its root two key goals: 1.) to develop a test and evaluation plan suitable to be an industry standard, and 2.) to use the plan to evaluate a specific device.

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To my loving wife,
Joyce,
for the many sacrifices she
makes for me each and every day.

OPERATIONAL TEST AND EVALUATION OF AUTOMATED CONSTRUCTION DEVICES

by

Lee R. Cranmer, B.S.C.E.

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas At Austin
in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in Engineering

THE UNIVERSITY OF TEXAS AT AUSTIN

April 1990

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Lee Reid Cranmer
April 1990

ABSTACT

OPERATIONAL TEST AND EVALUATION OF AUTOMATED CONSTRUCTION DEVICES

by

LEE R. CRANMER, B.S.C.E.
SUPERVISING PROFESSOR: DR. RICHARD L. TUCKER

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CHAPTER 1:

INTRODUCTION

1.1 Automation and Construction

The Random House College Dictionary defines automation as "the technique, method, or system of operating or controlling a mechanical or productive process by highly automatic means, as by electronic devices, reducing human intervention to a minimum."[1] The key here, is that automation reduces the human intervention of a productive process.

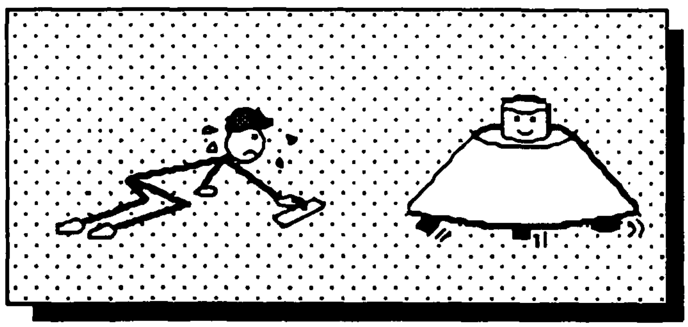


Figure 1.1 Human Intervention vs. Automation

Presently, the construction industry lags far behind other industries in its use of modern technologies to leverage worker production. Construction sites today require almost as much human intervention of the productive process as they did in 1950, while manufacturing and other industries have significantly reduced the negative effects of human intervention by embracing automation. Consequently, during the last fourty years, those industries have experienced rapid growth in individual productivity while at the same time construction's productivity has actually decreased.[2]

Stagnation in the use of advanced technologies, declining productivity, projected labor shortages, and spiralling costs associated with worker safety are crippling the construction industry. Bringing automation to the productive process of construction may be the solution to these problems and is an idea which is long overdue. Fortunately, today there is much research taking place worldwide to close construction's technological gap and bring "high tech" solutions to the job site.

1.2 Current Automation Hardware Applications in Construction

At present, there are at least 60 automated devices in various stages of development for the construction industry. In a compilation of current applications hardware, performed in the Fall of 1989, Claire Peterson organizes the devices into nine construction discipline areas and identifies their stage of development.[3] Although the compilation was limited by her access to published literature on the various devices, excluding those which are in design but not yet in public knowledge and those developed by manufacturers but not written up in scientific journals, insight into the scope of the expanding efforts to bring automation to construction can be gained by looking at her findings. Table 1.1 is a summary of her work.

Table 1.1 shows that the majority of equipment research to date has occurred in the areas of earthwork, concrete and piping. Due to an inherent absence of physical connections within the work - the material is continuous and uniform, and has relatively lenient tolerances - earthwork and concrete have probably seen a large amount of automation research activity because they are most likely the simplest disciplines to automate. Conversely, piping is inherently complex, has many

Table 1.1 Automated Construction Hardware (Fall 1989)

CONSTRUCTION DISCIPLINE	NUMBER OF DEVICES IN			Discipline Total
	Implementation	Prototype	Design	
Earthworks	5	3	1	9
Concrete	6	5	1	12
Piping	2	8	2	12
Material Handling	0	5	2	7
Electrical	1	1	0	2
Hazardous Mat'ls	3	2	0	5
Steel Erection	0	1	3	4
Masonry	0	1	2	3
Surface Coatings	1	4	1	6
Stage Totals	18	30	12	60

physical connections, is not a continuous material, and has strict tolerances. For these reasons, work in piping has not gone far beyond the prototype phase. But, given the difficulties in piping, why is there such an emphasis to automate its construction?

1.3 Motivation for Automation Research Today

In 1982, the Construction Industry Cost Effectiveness Project of the Business Roundtable identified piping as the construction discipline which had the greatest contribution to project costs and project problems.[4] Consequently, piping was identified as an area that if improved could have a significantly positive impact on project success. Thus, the motivation for trying to automate piping seems to be an effort to reduce costs, while the motivation to automate earthwork and concrete operations seems to be an effort to advance industrial development in areas which it is easiest to do so. What other motivators are there for performing automation research?

Mikell Groover states eight reasons to automate the manufacturing environment:[5]

1. Increasing Productivity
2. Reducing Labor Costs
3. Mitigating Labor Shortages
4. Improving Worker Safety
5. Reducing Raw Material Costs
6. Improving Quality
7. Reducing Lead Times
8. Reducing Inventories on Hand

For the construction environment one can add to these:[6]

9. Better Worker Utilization
10. Improved Work Environment
11. Mitigation of Hazardous Environments
12. Reduction of Jurisdictional Disputes
13. Superhuman Handling of Materials
14. Advancement of the Industry
15. Motivation of the Individual

Whatever the individual motivation, there is a blossoming interest in applying automation to construction. Others are successfully arguing the merits of individual applications of automation, this report will only say that automation is indeed on its way to almost every aspect of the construction site and the industry must prepare for its arrival.

1.4 The Need for a Standard Test and Evaluation Plan

In the 1990's, research efforts will flood the construction market with new equipment and processes, each promising to be

the ultimate in automated genius. How then, will tomorrow's manager begin to sort through the various claims of automation's benefits along with the dizzying array of new equipment, and distinguish the truly fantastic from the fizzle or the fraud?

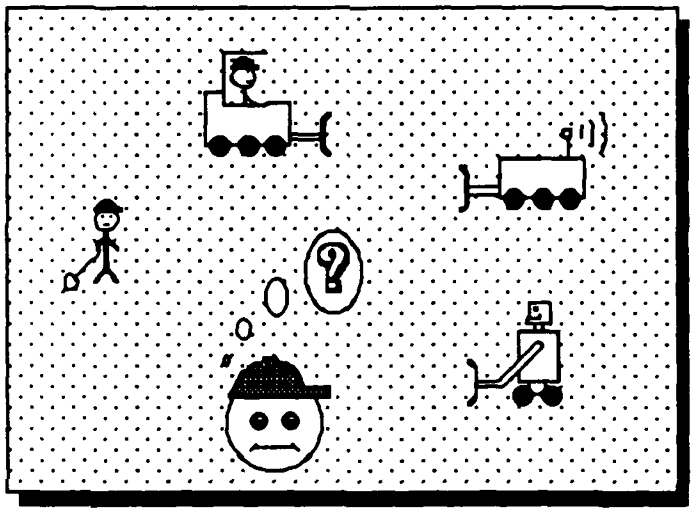


Figure 1.2 Tomorrow's Choices

The decision to develop or purchase automated equipment must be made thru a logical process. So then, how does one begin to objectively examine the overwhelmingly complex matrix of characteristics which differentiate new and old systems of equipment, materials, and methods? Beyond that, how can a fragmented industry pool its resources and share the valuable lessons learned by each other's research efforts?

The answer to both questions is to develop and use a standard test and evaluation plan for the systematic examination of automated devices. Owners, contractors, engineers, managers, rental agents or equipment manufacturers will find such a plan valuable in developing equipment and process specific test and evaluation programs to judge the effectiveness of individual automated devices.

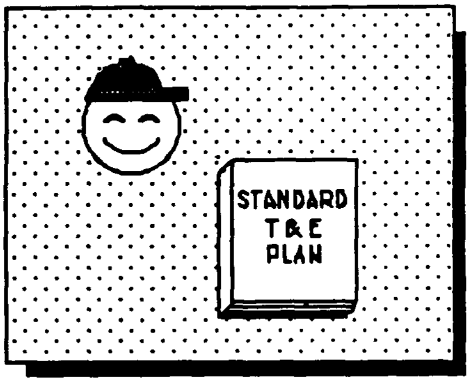


Figure 1.3 Today's Answer

1.5 <u>Scope of this Study</u>

In 1987 the Construction Industry Institute organized the Advanced Technological Systems Task Force. Its charter was to research the possibilities for implementing automation technology in the construction environment. Earlier efforts focussed on identifying specific tasks which were ripe for automation. This study has as its goals two key points:

1. To develop a test and evaluation plan suitable to be an industry standard for the examination of the merits of newly developed automated devices.

2. To use the plan to test and evaluate a specific automated device.

The University of Texas secured the loan of a remotely controlled concrete floor finisher manufactured in Japan to serve as the automated device used to varify the standard plan. Testing of the remote controlled trowel was performed at various University of Texas sites and on active construction jobs in the surrounding Texas area between April 1989 and March 1990.

This document reports on the development of the standard operational test and evaluation (OT&E) plan and the results of the OT&E of the automated trowel. Figure 1.4 represents the organization of this study.

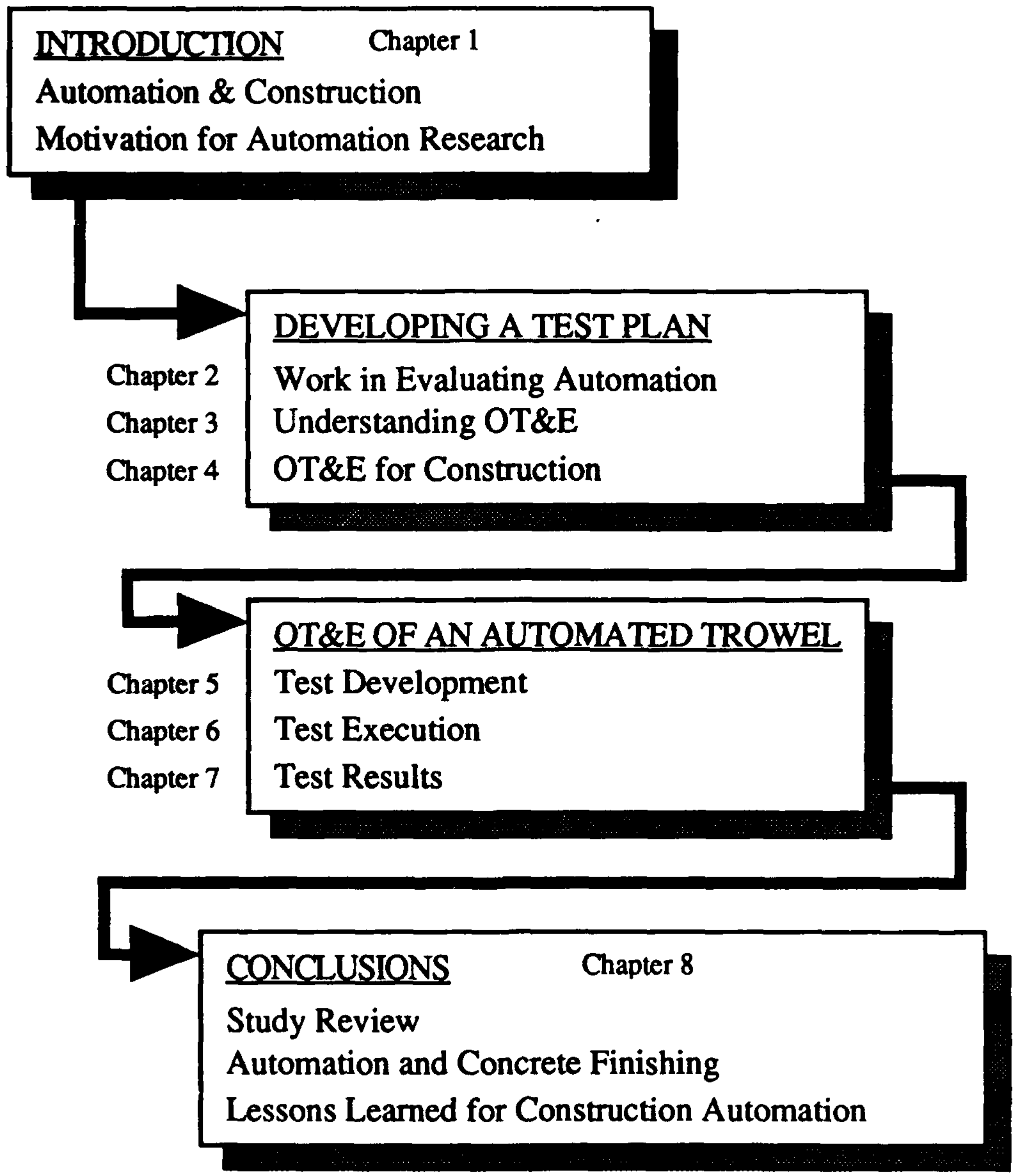


Figure 1.4 Study Organization

CHAPTER 2

AUTOMATION EVALUATION WORK TO DATE

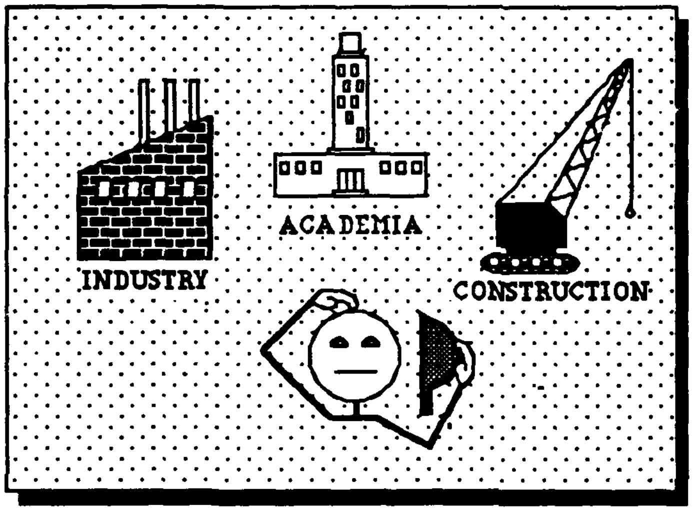


Figure 2.1 Where to Look for Test and Evaluation Examples

2.1 Where to Start?

The first step in the development of a standard test and evaluation plan is to assess the opinions of the eventual users of such a plan. After looking to the construction industry itself for test and evaluation (T & E) programs presently in use, its is appropriate to examine other industries for parallel programs and finally to look to academia for the newest in ideas on the subject.

2.2 Work in the Construction Industry

In the construction industry at large, there exists little published evidence of any work by equipment manufacturers, owners, or contractors in the area of evaluation of automated devices. Considering the void of information, is there anything to be gained by examining work in other industries?

2.3 Work in Other Industries

2.3.1 Work in Manufacturing

The industry which has seen the greatest amount of automation implementation is manufacturing. However, the majority of evaluation systems developed for manufacturing have their roots in business theory. Consequently, they measure the value to a decision maker strictly in monetary based terms such as profit or rate of return. These systems completely exclude the evaluation of characteristics which are difficult to put into monetary terms, such as quality, safety, reliability, and user comfort and fail to address the automation motivation issues identified in Chapter 1 as being unique to construction industry.

Two researchers, Troxler and Blank, have tried to take non-quantifiables into account through the use of multiple factor decision analysis and a mathematical model which translates non-monetary measures into monetary value.[7] They divide system value into four attributes: Suitability, Capability, Performance, and Productivity. These attributes are reduced to Determining Factors, such as Reliability and Availability, under the attribute Capability. Each Determining Factor is assigned a corresponding indicator of worth. Worth is then calculated by making a subjective determination of ranking with relation to maximum achievable for the indicator and adjusting the rating with a weighting factor for relative importance. Further weightings are assigned as the factors and attributes are combined and a total worth of the system is calculated through the application of traditional decision tree and probabilistic decision analysis.

2.3.2 Work in Aerospace

The development of advanced aircraft and space vehicles has necessitated the inclusion of automation into cockpits and space vehicle environments. NASA has sponsored a fair amount of research in the evaluation of A & R systems. The majority of published work has been specifically in relation to the man-machine interface and the allocation of tasks between man and machine.[8.,9,10] No references were found which try to encompass the entire spectrum of attributes which must be considered in evaluating automated devices.

2.3.3 Work in Defense

The most valuable information found in publicly available literature from the defense industry are the guidelines published by the services for contractors developing systems procured by the Department of Defense. Although not specifically directed toward automation, there are detailed guidelines for the planning, implementation, and management of T & E programs for the research, development, and performance evaluation of all types of devices and systems.

An example of these guidelines is Air Force Regulation 80-14, Research and Development Test and Evaluation, which serves as a good introduction to T & E programs. Other regulations and military standards give specific guidance for such related topics as Developmental T & E, Operational T & E, and for the performance of detailed failure analysis.[11,12,13]

2.4 Work in Academia

There have been relatively few academicians engaged in the evaluation of automation and its application to construction.

Their work has primarily been to open the eyes of the construction industry's members to the benefits of automation on the job site. The following is a categorization of their work.

2.4.1 Identifying Tasks With the Greatest Potential

Due to the infancy of automation research in construction, the majority of work has dealt with the identification of work disciplines and tasks which have a potentially high payback for automation research.

The Construction Industry Cost Effectiveness Project, performed by the Business Round Table (BRT) in 1982, rated seventeen construction areas according to their contribution to project cost and number of difficulties they present to contractors, thus identifying areas ripe for automation research.[14] The Construction Industry Institute's Advanced Technological Systems Task Force used the foundation laid by the BRT to identify specific tasks within the areas of structural steel, piping, and electrical work. Tucker, et al performed detailed activity sampling and surveyed construction participants to determine the tasks of greatest automation potential based upon the CICE's original criteria, proportion of project cost and amount of difficulty to the participant.[15] Work in identifying construction tasks for automation has also been performed by the following individuals:

Warszawski and Sangrey examined possible applications by first looking at the main features of present industrial robots, then matching their capabilities with requirements for performing construction tasks.[16]

Fazio proposes an automation index based on quantifiable ratings for need, technical and economic feasibility, and worker resistance, to determine automation potential.[17]

Kangari & Halpin first identifyed 33 potential construction tasks through a group brainstorming session, then subjectively rated each on 18 criteria under the headings of need and technical and economic feasibility. This resulted in normalized weighted averages which rank the 33 tasks according to their automation potential.[18]

Kangari has also individually worked on a knowledge-based expert system which captures the experience of professionals through information collected at workshops conducted at Georgia Tech. The Knowledge Based System examines level of repetitiveness, cost effectiveness, technological feasibility, productivity improvement, level of hazard, union resistance, and quality improvement. The result is a set of recommendations as to whether a task should be roboticized.[19]

Also proposing a KBS to aid in the decision to automate is Pagdadis. He examines four automation drivers: productivity, safety, quality, and superhuman handling, using subjective weightings and extensive activity modeling to determine an index of automation potential.[20]

2.4.2 Defining Automated Device Characteristics

Some work has been published in an effort to stimulate interest in the area of construction by automated hardware researchers.

Paulson describes the needs for and potential uses of specific hardware technologies on the construction site.[21]

By choosing a specific automation application and envisioning machine characteristics through a systematic breakdown of required functions, Skibniewski calculates a quantitative, deterministic measure of machine requirements based on available technology.[22]

2.4.3 Evaluating Automated Devices

The newest area of construction automation research is in the evaluation of specific devices to determine their application to the actual workface.

Halpin et all suggest the use of activity simulation of the pre and post automated state to predict behavior, optimize performance, and compare alternatives[23].

Skibniewski has what may be the most promising technique for evaluation. The Construction Robotic Equipment Management System (CREMS) is a knowledge-based expert system for comprehensive robot management. The system performs evaluations by working through four major components. First, a detailed analysis of the present construction task is performed. Then, the robotic device's capabilities are systematically analyzed. After comparing the task with the robot's capabilities and determining physical feasibility, an economic evaluation is performed to determine cost effectiveness. Once the robot is proven to be physically and economically desirable, the final component optimizes the scheduled use of the device.[24]

Table 2.1 Summary of Evaluation Work to Date

Evaluation Planning	
DoD	- T & E Management, Failure Analysis
Identification of Tasks	
Tucker, et al	- Matched High Cost Areas with High Problem Areas
Warszawski and Sangrey	- Matched Present Robot Capabilities with Task Performance Requirements
Fazio	- Quantifiable Index
Kangari and Halpin	- Subjective Ratings
Kangari	- Knowledge-Based Expert System
Pagdadis	- Knowledge-Based Expert System
Defining Device Characteristics	
Paulson	- Matched Present Robot Capabilities with Task Performance Requirements
Skibniewski	- Quantitative Measure of Requirements vs Available Technology
Evaluating Devices	
Troxler and Blank	- Multiple Factor Decision Analysis to Compare Systems
Halpin et all	- Activity Simulation to Compare Systems
Skibniewski	- Multiple Factor Decision Analysis with an Expert System to Compare Systems

2.5 What Comes Next?

The summation of work to date in Table 2.1 will serve as the basis for the standard test and evaluation plan. References from the Defense industry appear to be good sources for structuring the overall plan, while work from the academic sector can supply a consensus for relevant criteria and measures for the evaluation of automated construction devices.

CHAPTEP 3

UNDERSTANDING OPERATIONAL TEST & EVALUATION

3.1 <u>Introduction to Test and Evaluation</u>

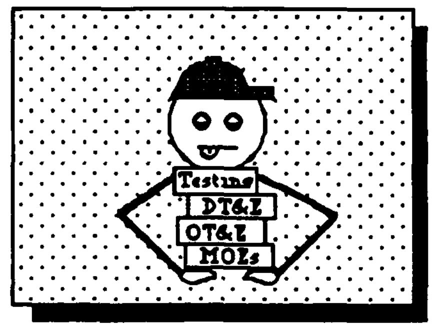


Figure 3.1
Understanding Test and Evaluation

Our nation's defense agency has been in the business of testing and evaluating new systems, equipment, and methods of operation for over two hundred years. Survival and the maintenance of a competitive edge (not only for the agency but at times also the free world) have hinged upon the ability to make the right decision when faced with a myriad of research, development, and deployment options. When facing the same type of decisions in the construction industry, the accumulated experience of the Department of Defense should be utilized. So, a good place to begin is to look at how the U.S. Air Force manages its operational test and evaluation programs.

Air Force Regulation 55-43, <u>Management of Operational Test and Evaluation</u>, outlines the principals and procedures used to promote consistent test and evaluation throughout the Air Force, Air Force Reserves, and the Air National Guard[25]. AFR 55-43 serves as an excellent guide for understanding the basics of test and evaluation and is the principle source for this introduction.

3.2 Types of Test and Evaluation

Developmental Test and Evaluation (DT&E) - Conducted to demonstrate that the system engineering design and development is complete, that design risks have been minimized, and that the system will perform as specified.

Operational Test and Evaluation (OT&E) - Is performed to estimate a system's operational effectiveness and suitability, to identify any operational deficiencies, and to identify the need for any modifications. OT&E begins as early as possible, is conducted under actual field conditions, and may continue throughout the system's life time.

Figure 3.2 shows the overlap of developmental and operational test and evaluation through the lifecycle of a system.

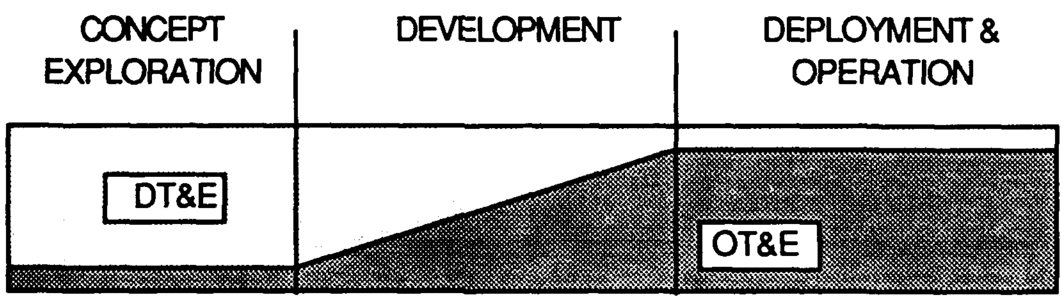


Figure 3.2 Life-Cycle Test and Evaluation

3.3 Purpose of Operational Test and Evaluation

Operational Test and Evaluation (OT&E) is conducted to ensure that new systems (systems can be individual equipment items, new work methods, or an entirely new material/

equipment process) meet the user's needs, operate satisfactorily, and are supportable under actual field conditions. Testing, conducted under actual field conditions, assesses and reduces acquisition risks and estimates the operational effectiveness and suitability of the system. Decision makers depend on the evaluations to choosing whether or not to proceed with developing, buying, modifying, or deploying a system.

3.4 Advanced Planning for OT&E

Advanced planning determines the purpose and scope of the test program, identifies the critical operational issues to be examined, develops test objectives, establishes a test approach, and estimates resources required for OT&E.

3.5 Developing a Specific OT&E Approach

The test approach for the evaluation of specific systems depends on an understanding of the system's planned operational concept, operational environment, and its intended performance capabilities and limits. The following should be considered when developing a specific approach:

Critical Operational Issues - What effects the use of current systems and would be most impacted by the new system's deployment?

Scope and Limiting Factors - The study's scope is defined and limited by first examining the critical operational issues and their supporting objectives and then assessing available resources and time.

Test Objectives and Subobjectives - What must data be collected on to evaluate the critical issues?

Test Concept - A road map which provides linkage between critical issues, areas of risk, test objectives, actual testing, data analysis, and final evaluation. A common format for the test concept is a flow diagram similar to the one shown in Figure 3.3.

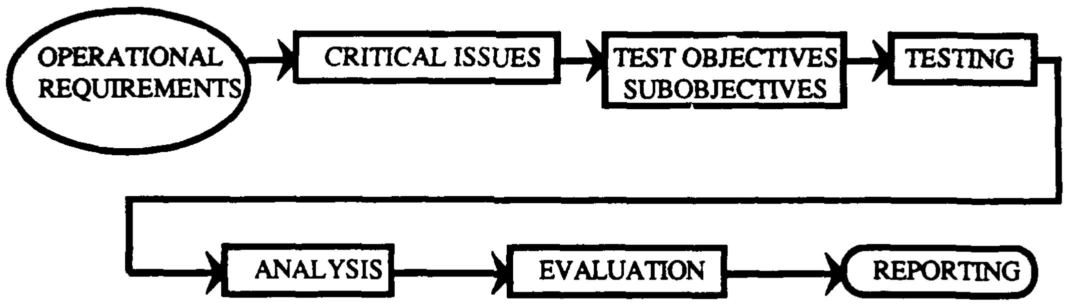


Figure 3.3 Test Concept Flow Diagram

Measures of Effectiveness (MOE) - A qualitative measure of a system's performance of a task or ability to meet a specified objective.

Data Requirements - After developing specific test objectives and measures of effectiveness, the planner now has sufficient information to determine what data is required from the tests. The data must be strictly based on the system's operational requirement and measure of effectiveness. Once established, the requirement should remain constant, even though the method of obtaining the data may vary.

Data Management - Data collection techniques are devised from an understanding of the data requirements list. Processing and data reduction techniques are identified as well as a plan for analysis and final reporting.

3.6 Evaluation of Test Data

After the test plan is put into action and the data starts flowing in, the OT&E approach should first be evaluated for its adequacy in testing the particular system. Once adequacy of the test program is established, the system itself can then be judged by analyzing the data gathered to assess its performance.

System Assessment - At first, the test team must compare the individual test results against the evaluation criteria and critical operational issues. Using its expertise, the team judges the actual performance in the test environment against the system's potential in the operational environment, thus assessing the appropriateness of the test program.

Data Analysis - Involves the application of preselected, disciplined techniques to judge the performance of the system while it is being tested. There are two basic types of data:

1. Quantitative Data - Measures of Effectiveness which can be expressed numerically are most often treated mathematically using a form of statistics.

2.

Qualitative Data - MOEs which represent subjective expression of preference of opinion are analyzed by a range of techniques from a conversion of opinion into numeric values for statistical analysis to establishing a consensus of opinion. The most common method is to establish an expert consensus of opinion and support it by simple mathematics which express the group decision.

CHAPTER 4

OPERATIONAL TEST AND EVALUATION OF AUTOMATED CONSTRUCTION DEVICES

4.1 Identifying Construction's Critical Operational Issues

The first step in developing a specific OT&E approach is to examine the critical issues which impact the decision to use a specific device. The issues which determine the appropriateness of the use of an automated device on the construction site can be grouped into five major areas of concern:

1.) Project Environment Interaction,

2.) System Performance,

3.) Economic Performance,

4.) Human Interaction, and

5.) Business & Societal Interaction.

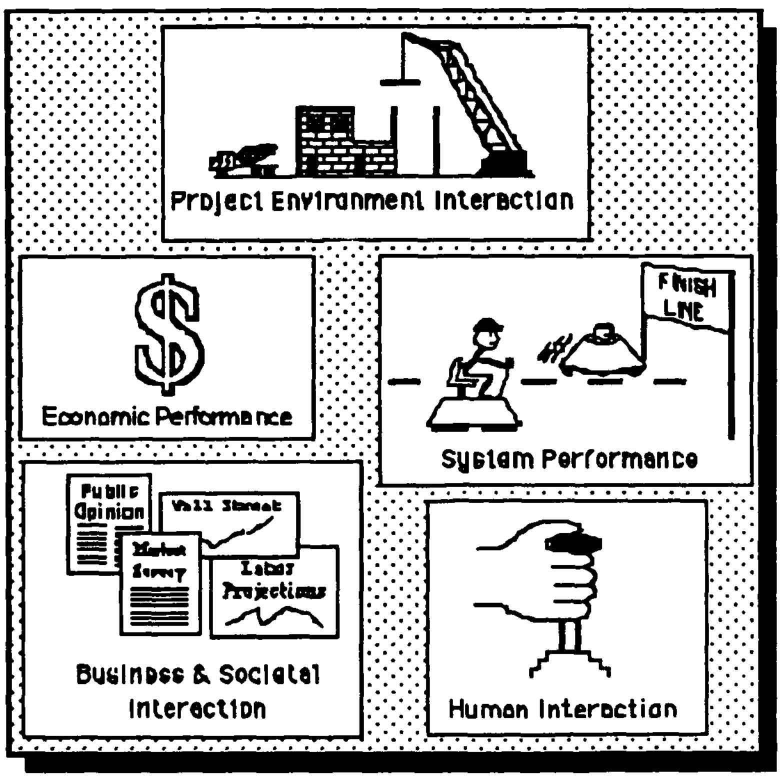
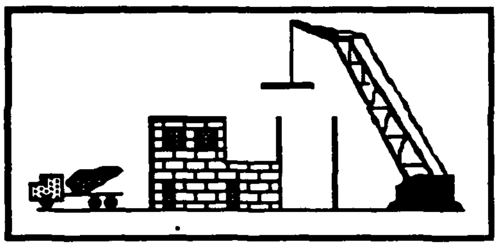


Figure 4.1 Construction's Critical Issues

The following is a brief discussion of those five major areas along with listings of specific issues for each compiled by the CII Advanced Technological Systems Task Force between March and September of 1989.

4.1.1 Project Environment Interaction



The present way of performing a construction task must be fully understood and compared with the proposed method. Start by examining the physical environment in which the task is performed and understand the limitations imposed by physical boundaries and access. Investigate the full nature of the work. Is the task performed only seasonally or intermittently? If so, is this due to the weather, climate, or another reason. What are the present methods, materials, equipment, labor, specifications, etc.? What is the average present production rate? Why is the present quality level specified?

Once the present method is fully understood, examine how the system will impact total operations. Aside from the device's ability to fit into the present physical environment and its impact on labor, material, support, and quality, how does it impact the total job? How does management fit into the picture? What impact on material and information supplies will the new method have? Must the Project Manager be concerned with the interface of the new process on other activities? Are there any gains made in the ability to acquire data which can be used for real time management control?

Next, examine how the design process will be changed. Is there room for improvement by making changes to the basic design choices, specifications, or the way they're conveyed? Will the new process allow for any slack in the delivery time of technical data? Will procurement need to change any of their material acquisition practices?

Finally, what are the worst out-comes and their associated probabilities of the possible failure modes of the new device? How do these compare with the present way of doing things? Will present safety measures become unnecessary when the new process is implemented? Is there a change to the way minor breakdowns effect the work crew or the way major failures impact other crafts? These questions are addressed by performing a failure analysis. MIL-STD-1629A sets out the procedures for performing a Failure Mode, Effects and Criticality Analysis (FMECA).[26] The following is a list of items to consider in evauating Project Environment Interaction:

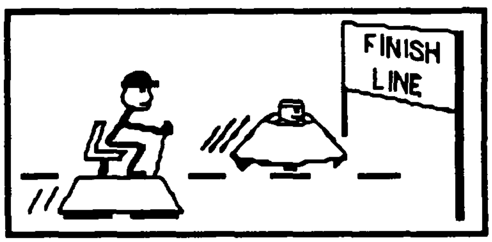
A. TASK ANALYSIS
1. Physical Layout
2. Seasonality & Varibility of Work
3. Present Methods & Materials
4. Present Equipment, Labor, &Specs
5. Present Production Rates
6. Required Level of Quality
7. Impact of Weather

B. IMPACT ON PROJECT MANAGEMENT
1. Material Supply
2. Schedule
3. Work Element Integration
4. Controls & Data Acquisition

C. IMPACT ON DESIGN & PROCUREMENT
1. Methods & Materials
2. Drawings & Specifications
3. Timing

D. IMPACT OF POSSIBLE FAILURE
1. Probability of Worst Case Safety Hazard
2. Delays from Minor Breakdowns
3. Disruption of Other Crafts

4.1.2 System Performance



The realistic capabilities and limitations of an automated device must be defined through testing under both "laboratory" conditions and actual field conditions.

Field Testing - Will define the performance limits of the particular new device and give insight into the consequences of these limits. It should include multi-level data gathering - pictures, video, performance data, industry comments, etc. Testing should confirm the device's ability to meet present specifications and levels of quality. Trade-off analysis should be performed on excesses and short-falls in areas such as production and operability. Also, the impact on inspection operations should be noted. Keep an open mind in order to recognize easy ways to remove any limitations discovered.

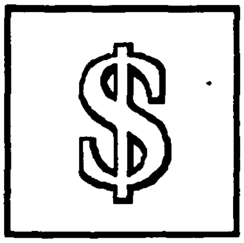
Lab Testing - A systems engineering approach must be taken to the analysis of machine and process components. The reliability, maintainability, and repairability of each component

must be predicted through the performance of a FMECA, the first purpose of which is to identify all catastrophic and critical failure possibilities so that they can be eliminated through design correction.

In short, the field testing will show the abilities of integrating the equipment into present operations, while the "laboratory" testing will help to imagine the order-of-magnitude improvements possible by either modifying the new machine or adapting present operations to the new equipment and process. Critical issues of System Performance are:

A. PRODUCTION RATE
   1. Continuous & Peak
   2. Work Envelope/ Flexibility
B. QUALITY
   1. Ability to meet Specifications
   2. Consistency of Meeting Specifications
   3. Required Inspection
C. OPERABILITY
   1. Required Transportation
   2. On Site Mobility
   3. Set Up & Break Down Time
   4. Required Clean Up
D. RELIABILITY
E. AVAILABILITY
F. MAINTAINABILITY
   1. Spares Availability
   2. Technical Knowledge Required
G. DURABILITY
H. PORTABILITY

4.1.3 Economic Performance



Capital investment criteria, such as rate of return or uniform cost per unit of production, should be utilized to evaluate any new expenditure of a company's resources. Skibniewski proposes the use of Net Present Value (NPV) to determine an attractive maximum purchase price for the contractor when considering an automated device. The NPV should be based on the costs (initial cost, economic life, and operation expenses over and above the present method), benefits (labor savings, health benefits, quality improvement, productivity improvement, and activity extension); and a Minimum Attractive Rate of Return (MARR) usually somewhere between 10-25%.[27]

Rehg claims that for use in automating manufacturing, an application must pay for itself within two years by primary cost savings from direct & indirect labor.[28]

Whichever system and criteria are chosen to judge economic performance, careful consideration must be taken when projecting maintenance and downtime costs since the equipment in question will most likely be one-of-a-kind and have a limited work history. A look to the manufacturing sector and at similar automated systems can be made to help with the estimation of future operational costs. Some specific critical Economic Performance issues to consider are:

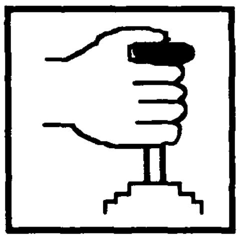
A. COSTS
1. Acquisition
2. Operating
3. Maintenance

4. Breakdown, Downtime & Back-up
5. Overhead
    a. Taxes & Insurance
    b. Support Equipment
    c. Training & Transportation
    d. Set Up & Clean Up

B. BENEFITS
1. Labor Savings
2. Health Benefits
3. Quality Improvement
4. Productivity Improvement
5. Activity Extension

C. EQUIPMENT PHYSICAL & ECONOMIC LIFE

4.1.4 Human Interaction



Isaac Asimov proposed Three Laws of Robotics: 1.) A robot must not harm a human or allow one to be harmed, 2.) A robot must always obey humans, unless this conflicts with rule 1, and 3.) A robot must protect itself from harm, unless this conflicts with rules 1 & 2.[29] Certainly, these rules also apply to automation and are the basis for examining the critical factors of human interaction.

Closely examine any potential improvements made in the areas of risk to the operator, other crew members, other crafts, and neighbors to the site. Are there any changes in the types of hazards encountered, either by injury or long-term exposure? Does improvement in reducing operator risk offset any increased production costs? Aside from safety, factor's also influencing a decision to automate include the new method's operator skill, comfort, and control characteristics.

The automated equipment may require the knowledge of additional skills by the operators and maintainers. The operators might not only need to be experienced in the traditional construction method, but may also have to be comfortable with advanced machine controls. Conversely, the new equipment and its controls may simplify the task to a level where formally required skills are no longer needed. Keep in mind, the design of the actual controls will greatly influence the acceptance of the machine by the work force, the required training by its operators, and the back-ground required of the maintenance personnel.

Does the new method offer any improvements to the comfort of the operator? Does it eliminate any noise, vibration, or dirt which impacts present productivity levels? Does it change the conditions under which the worker can perform, such as enabling work under adverse weather or climate or allowing work to be performed during a day shift which was presently performed at night. Improving the comfort of the worker may cause an equal improvement in their output potential.

Lastly, look at the present level of task automation and judge wether the proposed level is appropriate to the task. There may be other tasks in the operation which should be addressed first for the greatest improvement to overall productivity. Human Interaction concerns include:

A. SAFETY
  1. Impact on Operator
  2. Impact to Others On & Off Site
B. REQUIRED SKILL
  1. Educational Background

2. Required Training
3. User Friendliness

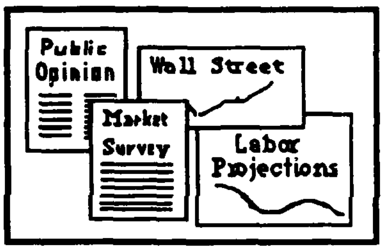
C. COMFORT

1. Noise, Lighting, Vibrations & Dirt
2. Time of Day, Climate, & Weather

D. LEVEL OF AUTOMATION

1. What is the Present State?
2. What is Offered?
3. What can be justified?

4.1.5 Business and Societal Interaction



A new process always impacts not only the immediate worker, but also the surrounding community. The use of a specific method must not only be acceptable by the client, but also by the public. Something to consider, any automated device which passes the public acceptance test should be able to be used as a marketing tool for new business.

The competition may dictate that a contractor take riskier propositions, or other than "bottom line" considerations on automation implementation. Availability of present required worker skills vs those needed by the contemplated process need to be projected. Also, when looking at labor, the resistance to change by the labor force and the specifics of integration will also come to bear on the decision.

Future availability of the new equipment, spare parts, and maintenance support should also be known. Can adequate

supplies be delivered? Will the producer be around to support the equipment down the road?

Finally, the firm faced with the automation purchase decision, be· it a general contractor, specialty subcontractor, rental yard, or owner, has a unique motivation for examining the automated device in the first place. This motivation and the individuals perspective will have a great impact on the interpretation of the over-all evaluation. Their business volume, seasonality, stability, cash reserves, research posture, and attitude toward risk will all come to bear on the final decision to buy into the new method. Dealing with risk in the decision making process is an issue all its own. Researchers such as Skibniewski suggest the use of Multi-Attribute Utility Measurement to aid in the formulation of a final decision.[30] The following is a list of Business & Societal Interaction concerns:

A. SOCIAL/ CULTURAL ACCEPTANCE
   1. Marketability
   2. Client Acceptance
B. MARKET PRESSURES
C. LABOR PICTURE
   1. Present & Future Availability
   2. Resistance
   3. Integration Impacts
D. MACHINE AVAILABILITY
   1. Availability of Specific Machine
   2. Producer's Track Record
E. COMPANY'S CHARACTERISTICS
   1. Business Volume
   2. Automation Motivation
   3. Risk Preference

4.2 Test Development

The organization undertaking the testing must now examine its technical abilities, available resources, and evaluation motivation in order to ascertain the individual testing program's scope and limiting factors as well as the test objectives and concept. The specific device under evaluation will dictate the MOEs and data collection requirements.

4.3 Data Collection and Management

Data can be collected through standard observation techniques such as time lapse video taping, stop watch studies, and work sampling for productivity analysis or crew balance. The most valuable data collection techniques are the interview and questionnaire. By surveying the attitudes and opinions of operators, contractors, owners, engineers, and competing equipment manufacturers, an assessment of the device's real value and potential difficulties can accurately be made.

Collecting performance data can best be accomplished by judging the automated device directly against the present method of operation. This is done by: 1.) selecting a representative task to be performed, 2.) judging the operator's experience level, 3.) repeatedly measuring the operator's completion time on new and old systems, and 4.) plotting of completion times versus task iteration. The result shows the learning curve and compared peak production rates between the new and old systems.

Care must be taken to ensure that the data collected are unbiased and that results are not skewed through improper analysis techniques.

4.4 System Assessment

Before evaluating the performance of a new device, ensure the appropriateness of the test program's data collection techniques and data analysis tools.

4.5 Analyzing and Reporting Results

The finished report should present the purpose and background of the OT&E program, including a complete history and description of the system, and should describe the actual tests performed and analyze the operational effectiveness and suitability of the automated device.

It is recommended that when presenting the evaluation to the industry at large, that the analysis be presented as a multi-attribute listing of costs and benefits, comparing the automated device with traditional methods. Physical and economical envelopes of operation should also be derived, and great care should be taken not to reduce qualitative data to a meaningless index number, but to allow the reader and their individual risk perspective to decide the merits of the new process.

4.6 Following Up

If the automated system proves to be both technically and economically feasible, and the decision is made to buy into it, the job of OT&E is not complete. Continuing evaluation of the applied system is necessary to identify problems requiring correction and to capture actual performance data to assist in future automation decision making.

CHAPTER 5

TEST DEVELOPMENT FOR AN AUTOMATED TROWEL

5.1 Initiating a Specific OT&E Appro ch

Section 3.5 points out that developing a specific test approach first requires an understanding of the present method's operational concept, environment, and capabilities as well as the intended performance limits of the new device. The goal is to perform an operational test and evaluation of a remote controlled concrete floor finisher. In order to develop a specific test approach, an understanding of the purpose and processes of finishing concrete floors, the environment in which finishing takes place, and the tools used to carry it out was first acquired. After becoming versed in the particulars of concrete finishing, the intended performance characteristics of the remote controlled trowel were examined before a defining the specific critical issues to be examined, scope, limits, objectives, and concept of the test.

5.2 Understanding the Basics of Concrete Floor Finishing

5.2.1 Concrete Floors: Prepping, Placing, and Finishing[31]

5.2.1.1 Preparation

To successfully place concrete floors requires much preparation. The slab must be properly supported and have uniform conditions underneath it in order to evenly set up

and perform as intended. Preparation for the placement of concrete floors on grade involves working the sub-grade and installing a sub-base, while elevated slabs first require the installation of adequate shoring before the erection of formwork.

Erecting the Forms - Forms should be accurately set, clean, tight, adequately braced, and lined with materials that impart the desired off-the-form finish. The forms need to be designed for removal with minimal damage and wood forms must be pre-wetted or oiled to prevent water absorption from the fresh concrete.

Reinforcement Placement - Reinforcing bars and any other embedded items must be clean and free of loose rust or mill scale when the concrete is placed.

5.2.1.2 Placement

Preparation for placing concrete floors starts with the ground breaking of the project and is completed usually the day before the scheduled pour, with fine-tuning of forms, reinforcing, and sub-base occuring as the pour progresses. The sequence of placement and finishing starts with these fine-tuning operations and isn't complete until the slab has cured. These operations are manpower intensive, continuous operations which usually last from early morning until late into the evening on days of scheduled pours. Figure 5.1 summarizes the placement and finishing cycle.

Delivery to the Immediate Location - Concrete should be deposited continuously and as near as possible to its final position thru the use of chutes, pumps, or hoppers. Placement should start along a perimeter at one end of the slab with each

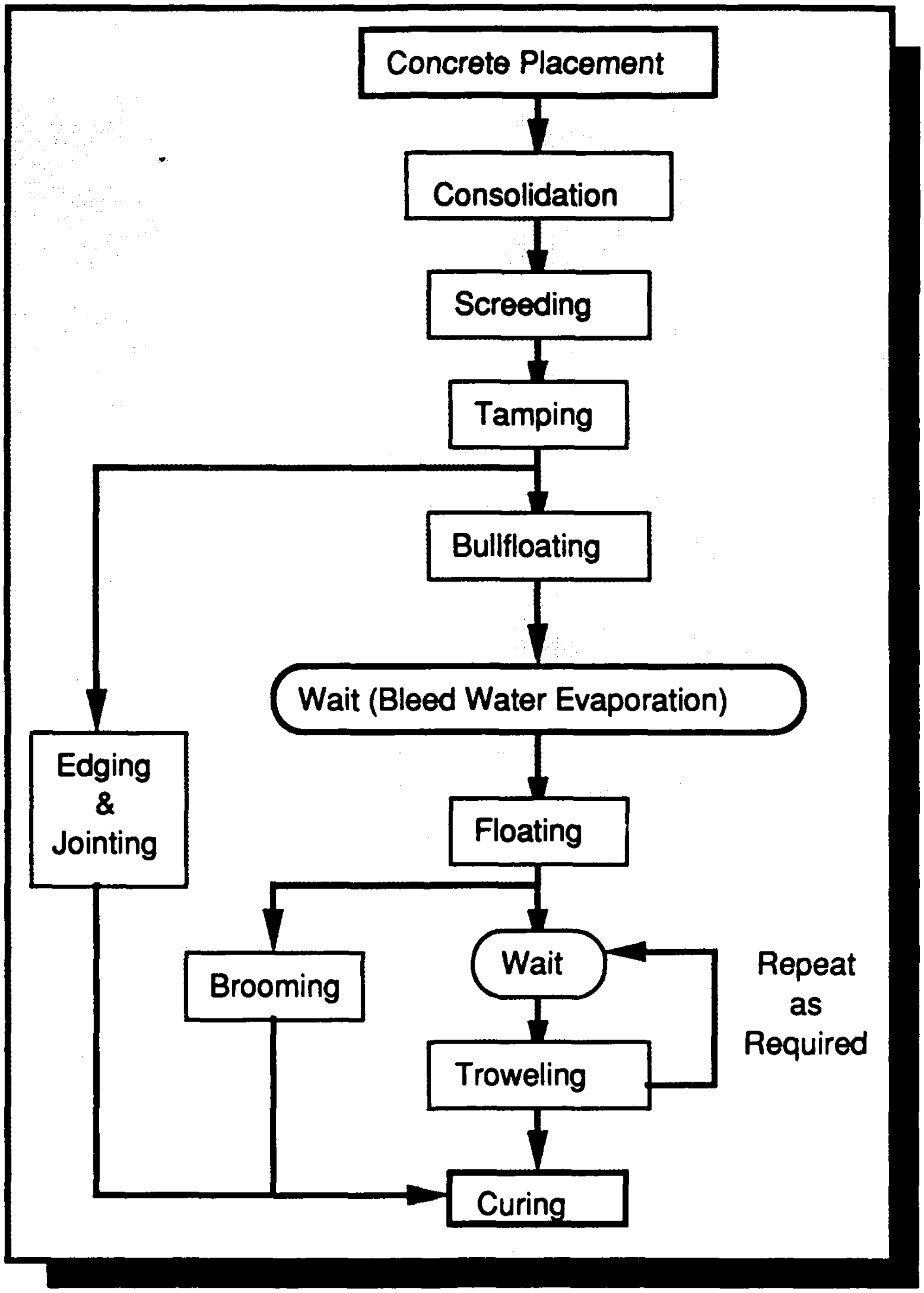


Figure 5.1 The Placement and Finishing of Concrete

batch discharged against the previous one and proceeding in a systematic matter.

Depositing Within the Immediate Area - Concrete should not be dumped in large piles then moved horizontally into position, such practice tends to segregate the mortar from the aggregate. Any final distribution can be performed by short-handled shovels or come-alongs (hoe-like tools).

Consolidation - Consolidation is the process of compacting fresh concrete to mold it within the forms and around embedded items and to eliminate stone pockets, honeycombs, and entrapped air pockets. This is accomplished by either hand rodding, spading, internal vibrators, or vibratory screeds.

5.2.1.3 Finishing and Finishing Tools

The finish imparted upon a concrete floor is dictated by the specifier in an effort to give the floor certain performance characteristics desirable for its intended use. The American Concrete Institute defines seven classes of floors and suggests finishing techniques for each based upon their eventual use.[32]. Table 5.1 presents those seven floor classifications

There exist other special classes of floors not covered by the ACI system, they include: floors with decorative coatings, floors requiring special skid resistance, and floors requiring electrical conductivity. ACI 301-84 covers the finishing of these special floors. However, Table 5.1 is still applicable to the vast majority of concrete floors produced today.

Knowing the proper sequence to follow and which tools to use is the key to meeting the specifications for each of these

seven classes of floors. The following is a general guide for the operations and implements used in concrete floor finishing.[33]

Table 5.1 ACI Floor Classifications

Class	Usual Traffic	Use	Special Considerations	Finishing Technique
1	Light foot	Residential/ tile covered	Grade for drainage, make plane for tile	Light steel trowel
2	Foot	Offices, schools, etc.	Nonslip aggregate mixed into surface	Medium steel trowel, special finish for nonslip
		Ornamental	Color shake	Medium steel trowel; color, exposed aggregate, wash if desired
3	Light foot and pneumatic tire	Drives, garage floors and sidewalks	Crown, pitch, joints, air entrainment	Broomed finish
4	Medium foot and pneumatic tire	Light industrial commercial	Careful curing	Hard steel trowel; brush for nonslip
5	Heavy foot and pneumatic tire	Industrial single course with integral topping	Careful curing	Hard steel trowel; special metallic or mineral aggregate
6	Heavy foot and hard tire, severe abrasion	Bonded two-course heavy industrial	Base: Textured surface and bond	Screed only
			Topping: Special aggregate and/or mineral or metallic shake	Repeated hard steel troweling
7	Classes 3,4,5,6	Unbonded toppings	Bond breaker on old concrete surface, 2.5-in min thick unbonded overlay	Finish according to traffic classification

Screeding (Strike Off) - Screeding cuts off excess concrete to bring the top surface of the concrete slab to the proper elevation. By pulling the screed forward and back and forth in a sawing motion, the final elevation of the concrete is struck off and leveled.

Screeds are also known as a staightedges or strike-off rods, and are usually a piece of lumber or lightweight magnesium and are sometimes fitted with a vibrating mechanism for consolidating the concrete. The screed should extend beyond the edge of the forms. If the pour is too wide, strike off pads and beams must be established in the middle of the wet concrete with the aid of a sight or laser level and measuring stick.

Tamping (Jitter Bug) - Tamping, when performed, immediately follows strike-off to embed the coarse aggregate into the concrete surface.

Tampers are also called jitter bugs or jukes, and consists of a 6-8 inch wide perforated metal platform attached to vertical handles.

Bull Floating or Darbying - Bull floating is performed immediately after strike-off.to eliminate high and low spots, embeds large aggregate and brings fines up to the slab surface., Bull floats are passed over the slab perpendicular to the forward travel of the screed.

Bullfloats consist of a wood, aluminum, steel, or magnesium platform typically 8 inches wide and attached to a long aluminum or fiberglass handle. The angle of the float head remains fixed in relation to the handle during use. Darbies are a

hand tool ranging in length from 30-80 inches with the same purpose as a bullfloat, but for confined areas.

Screeds, tampers, bullfloats, and darbies are constructed of materials which do not seal the concrete surface, but allow it to remain porous, enabling bleed water to rise to the top of the slab.

Bleed Water Evaporation - Only when bleed water sheen has evaporated and the concrete can sustain foot pressure with only about 1/4 in indention, is the surface ready for continued finishing. Any further finishing while bleed water is on the slab can cause serious crazing, dusting, or scaling.

Edging and Jointing - Edging densifies and compacts the concrete next to the form where floating and troweling are less effective, making it more durable and less vulnerable to spalling and chipping by producing a neat, rounded edge. Initial edging starts after bullfloating, but before bleeding occurs and proceeds through final trowelling.

Edgers are hand tools usually made of stainless steel and come in various shapes to produce the desired geometry at the edge of the concrete slab.

Proper jointing practices control shrinkage cracks. Jointers are used to cut the control joints into the concrete slab before it stiffens. Groovers or jointers, are similar in construction to edgers. Saw cutting these control joints at the proper time replaces the need for hand grooving.

Floating - Floating is performed only after bleed water has evaporated and the surface has sufficiently stiffened to accommodate the equipment. Floating seals and trues the

surface and prepares it for troweling or brooming. Floating embeds aggregate particles just beneath the surface, removes slight imperfections, humps, and voids, and compacts the mortar at the surface in preparation for additional finishing. Floating produces a relatively even but not smooth texture and is often used as a final finish.

Hand floats range from 12-20 inches in length and are made of magnesium, cork, rubber, or wood. However, floating is more commonly performed by machine with the use of either power floats or power trowels fitted with special float shoes.

Brooming - When a slip resistant surface is desired, Brooming follows floating to produce a shallow texture and takes the place of troweling.

There are brooms produced especially for finishing concrete with plastic bristles. Wire combs are also used when a deeper groove is desired.

Troweling - Troweling follows floating when a smooth, hard, dense surface is desired. The first troweling pass may produce the desired surface free of defects. However, surface smoothness, density, and wear resistance can all be improved by additional troweling passes and two or more successive troweling operations may be necessary to produce the desired surface.

Trowels are made of high-carbon steel or stainless steel, the hand held trowels come in various shapes and sizes to accommodate various surface geometries. Machine trowels are also manufactured and are available in walk-behind, ride-on, and automated configurations.

Curing - All newly placed slabs should be cured and protected from rapid drying, extreme changes in temperature, and damage from other operations. Curing ensures continued hydration of the cement and strength gain in the concrete.

5.2.2 Basics of Power Floating and Troweling[34]

The purpose of floating is to embed the coarse aggregate, remove humps and valleys and compact the concrete surface, while, troweling is performed only after floating to produce a dense, smooth, hard surface.

The most commonly used piece of equipment for both power floating and troweling is a 42 inch walk-behind power trowel. Figure 5.2 depicts the typical components of a walk-behind power trowel. Although less common, there are specialized machines exclusively for power floating which are similar to the walk-behind power trowel except that they have a revolving disc instead of blades and also incorporate compaction and vibration. These power floats are usually only used to float low slump concretes or toppings.

Since ride-on power trowels and automated power trowels all incorporate some form of the basic revolving blades found on the walk-behind models, an understanding of the floating and troweling principles used by all of the power trowels can be gained by examining the walk-behind model.

On the walk-behind power trowel, the blades of the machine finish the concrete as they swirl around the surface. For floating, the blades used are approximately 10 inches wide and have turned up leading edges so that they will not penetrate

or tear the fresh concrete surface. For floating, the blade angle is kept flat and the rotation speed is kept slow to further prevent tearing or gouging of the surface.

For troweling, the blades are approximately six inches wide and do not have turned up leading edges. During troweling, the blades are at first given a slight angle and the rotation speed is increased somewhat. On each successive pass, the angle is increased along with the rotation speed to exert greater pressure on the concrete surface. Figure 5.3 depicts the relation between concrete stiffness and trowel blade angle. This increased pressure allows the ever stiffening concrete to be reworked, producing molecular change and greater hardness in the slab surface.

It is desirable to use a systematic pattern when floating and troweling to ensure complete and efficient finishing. Power floating is started in a direction perpendicular to bullfloating and optimally runs from slab edge to slab edge, overlapping the previous pass by half the width of the machine. Floating and troweling will generally proceed along the slab following the same pattern used during the pour,

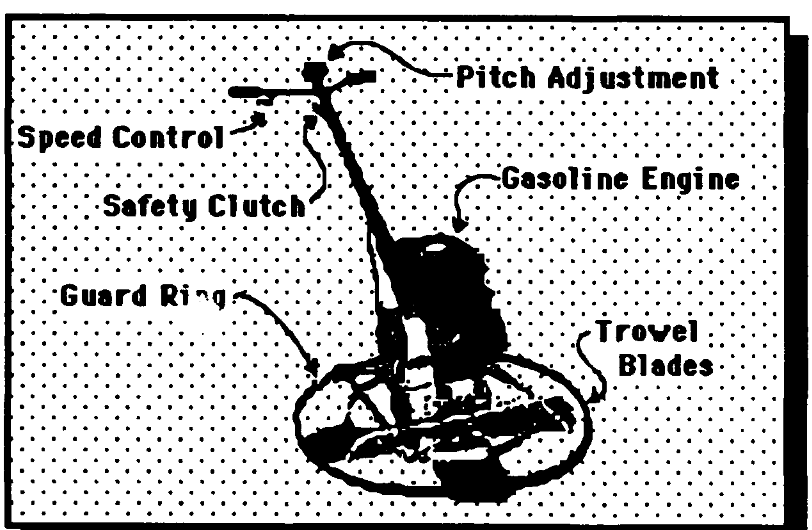


Figure 5.2 The Walk-Behind Power Trowel

since concrete stiffness is dependant upon the time since placement. So, a well planned pour pattern can optimize floating and troweling operations. Figure 5.4 shows well planned floating and troweling patterns.

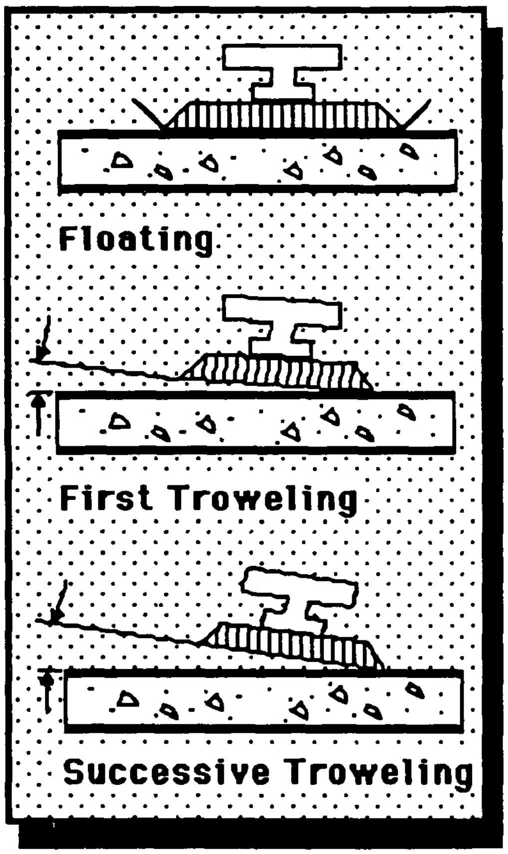


Figure 5.3 Blade Angle vs. Concrete Stiffness

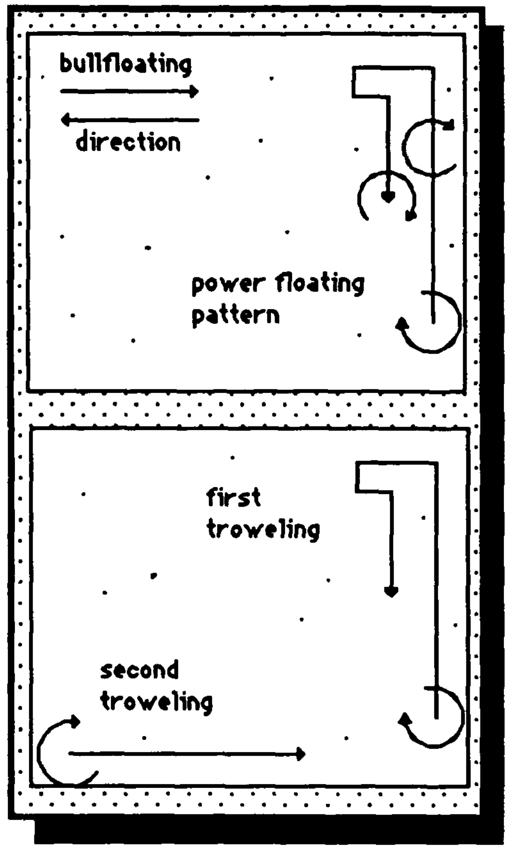


Figure 5.4. Floating and Troweling Patterns

Defects in the surface, such as humps or valleys, require the operator to use different finishing patterns for finishing. For example, because the blades on all walk-behinds rotate in a clockwise direction, low spots can be filled by moving the walk-

behind trowel around them in a clockwise direction while high spots are removed with a counter-clockwise motion. Figure 5.5 shows an example of how this is accomplished. Also, the operator must vary his finishing patter because some areas set faster than others, depending upon the consistency of the mix from truck to truck, areas of shade and sun, areas exposed to wind versus areas blocked from it, and non-uniform under-slab conditions.

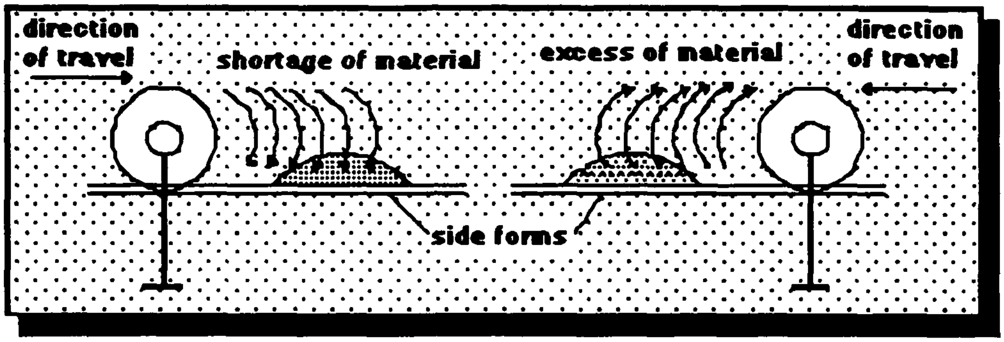


Figure 5.5 Correcting Defects With a Walk-Behind Trowel

5.2.3 Available Power Floating and Troweling Equipment

Floating and troweling of concrete surfaces has been performed by hand since the time of the Romans. In 1938, a concrete finisher from Boise, Idaho, tired of sore knees and a stiff back, attached a broom handle to a lawnmower engine rigged with trowels, thus giving birth to the first walk-behind power trowel. Marvin Whiteman's walk-behind was patented in 1939 and remained the only type of power trowel until 1973, when Butch Holts, then an employee of Master Trowels of Dayton, Ohio, had the idea of placing a seat on top of two walk-behinds, thus inventing the ride-on power trowel.

Master Trowels remained the exclusive producer of ride-ons until their purchase by Arrow in 1988. Since then, four other manufacturer's have joined Arrow-Master in the licensed sale of ride-on trowels in the United States.

The ride-on manufacturers began serious competitive development of the modern dual overlapping ride-on models in 1986. This was also about the time that four Japanese construction companies began the development of their own automated power trowels. Worldwide today, there are approximately thirty manufacturers of walk-behind power trowels, five manufacturers of ride-ons, and four automated trowels in the prototype or production stages.

Walk-Behind Power Trowels - The size of a walk-behind is expressed by its blade diameter,they range in size from 20-48 inches. Figure 5.2 shows the typical components of a walk-behind. The trowel blades are attached to a vertical shaft by a spider assembly, which is powered by a 3 to 11 horsepower gasoline engine. The handle has two hand grips which enable directional control: to move left, apply a slight upward pressure; to move right, press down slightly; to move forward, twist the handle clockwise; to move backward, twist the handle counter-clockwise; to stay in one spot, hold the handle in a neutral position. The blade pitch can be changed at any time and is controlled by a knob mounted at the top of the handle. Blade rotation can also be varied with the engine throttle mounted on the handle. Safety features include an automatic clutch and guard ring. Walk-behinds can be fitted with float blades, trowel blades, float shoes, or combination blades and range in price from $1500 to $2000.

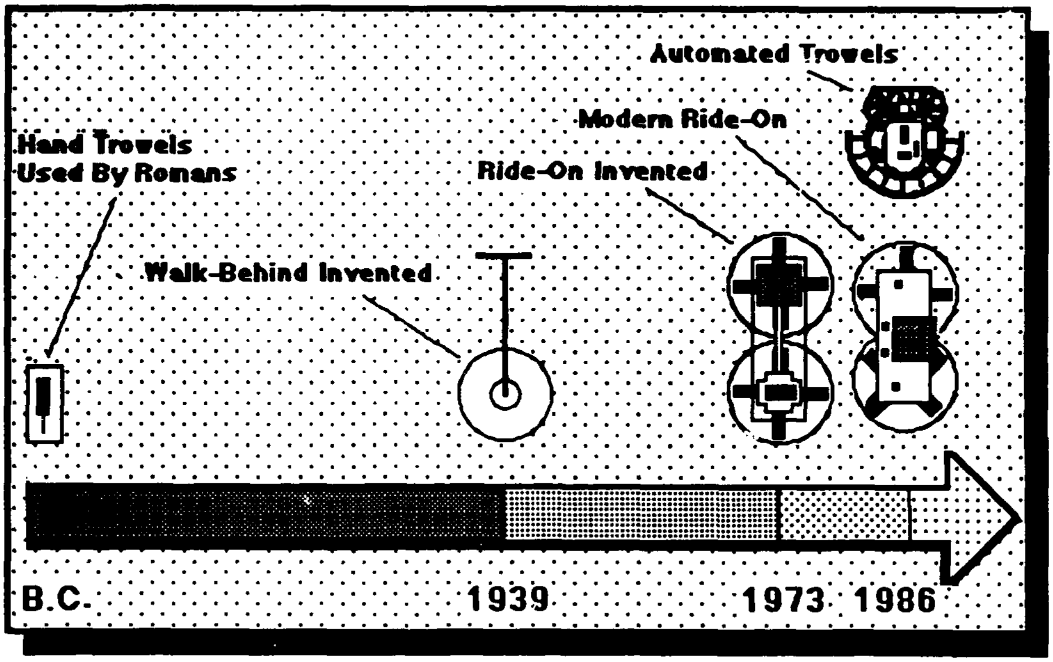


Figure 5.6 Trowel Development Time-Line

Ride On Power Trowels - Modern ride-on power trowels are typically machines with twin overlapping trowel heads from 36-46 inches in diameter. They range in weight from 320-890 lbs and utilize from an 18 to 23 HP gasoline engine to drive the blades. The trowel blades are connected to the motors with spider assemblies and fixed gear boxes. The machines are balanced for ease of control with the engine mounted in the center of the platform directly under the operator's chair. Most have independent pitch controls which can be adjusted at any time and are steered by dual hand controls: push both controls forward to go forward; pull both back to go backwards; move the right hand to the right to go right; move it to the left to go left; and twist the handles clockwise or counter-clockwise to spin the machine in the respective direction. All have electric starters, most have foot throttles, and safety features include dead-man

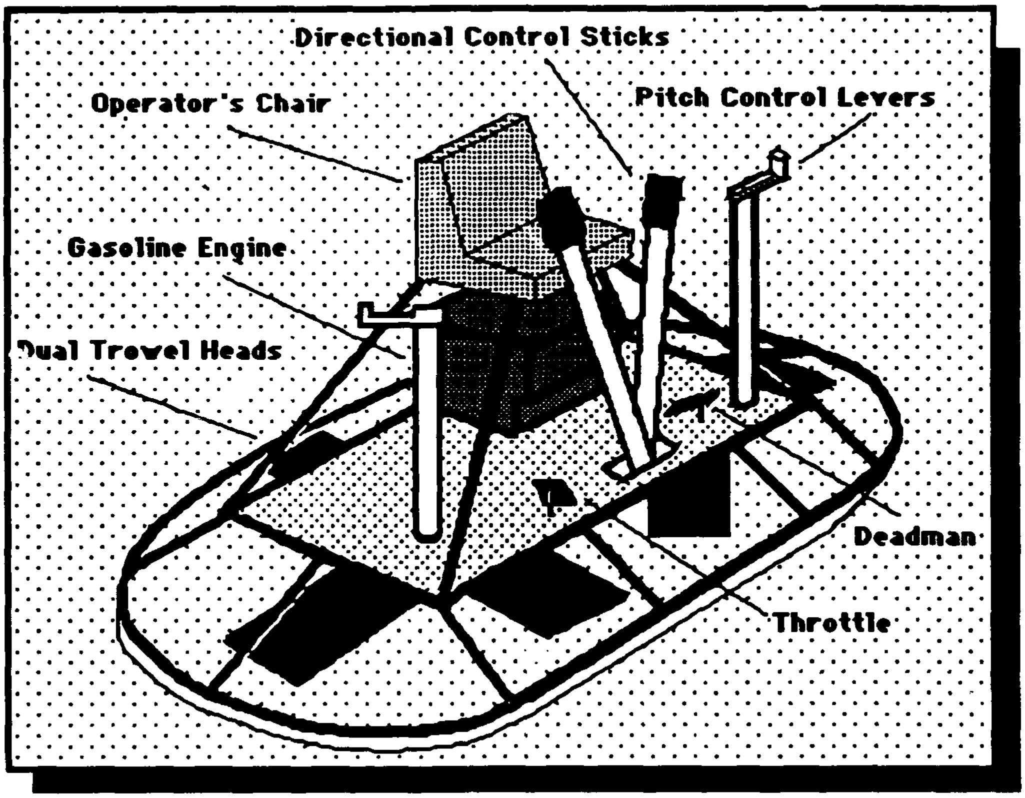


Figure 5.7 A Modern Ride-On Power Trowel

switches, slip clutches and safety guards. Most can be mounted with combination blades for both floating and troweling. However, it is recommended to use walk-behinds for floating and to wait to use the ride-ons for troweling since the weight of the machines require stiffer concrete to operate. Ride-ons are priced around $7000.

Automated Power Trowels - Kajima, Ohbayashi, Shimizu, and Takanaka corporations of Japan each have an automated power trowel in some stage of advanced development. The principle motivator for the development of automated trowels by four of Japan's largest construction corporations seems to have been the replacement of hand finishers. All four have

integrated a microprocessor into the directional control of the trowels, which is performed by electrically driven sponge rollers or tracks. Figure 5.8 shows the basic components of the automated trowels.

Two of the machines are radio remote controlled. One of these two is self contained, utilizing gasoline engines to power the trowel blades and supply electricity for controls and movement. The other radio remote controlled trowel is tethered to its power source by an overhead power cable.

One of the four trowels is semi-autonomous, using a gyro-compass and distance sensors to carry out pre-programmed directional commands. This machine is fully electrically driven and is also supplied with power by an overhead tethered cable.

One of the trowels is rather advanced. It has a self contained laser navigation system which can guide the machine within a pre-determined boundary and has an on-board gasoline engine which powers the trowel blades and supplies electricity for the electronics and drive wheels.

The four automated trowels have been used by their developing companies on hundreds of construction sites within Japan, and some are being sold to Japanese finishing specialty contractors. All machines are only designed for troweling and must be preceded by power floating, which is usually performed in Japan by walk-behinds. The estimated production costs of the machines range from $40,000 to $200,000 per unit.

5.3 Understanding the Remote Controlled Power Trowel

In April of 1988, The University of Texas at Austin secured the loan of one of the self-contained radio remote

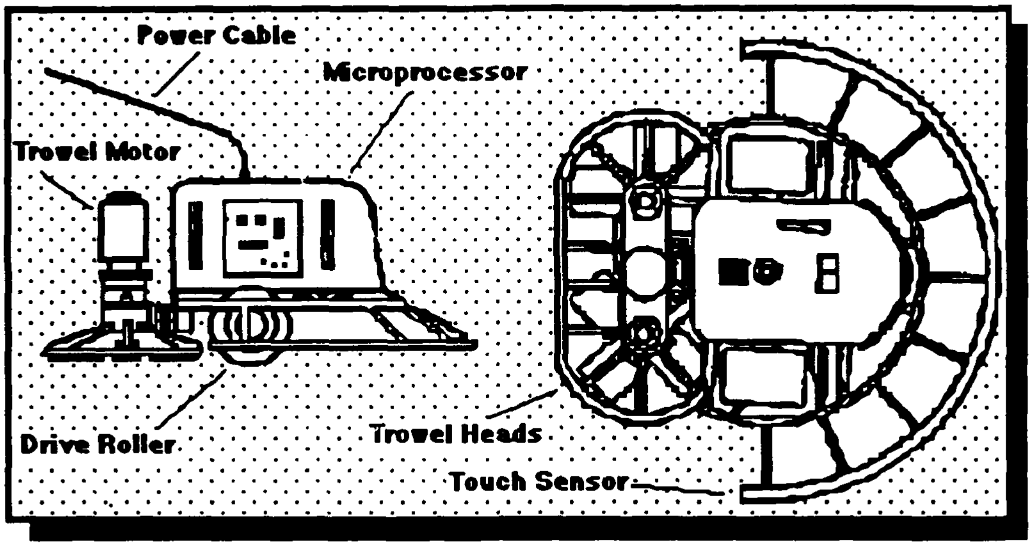


Figure 5.8 An Automated Power Trowel

controlled power trowels mentioned in the previous section. This loan was negotiated through the Advanced Technological Systems Task Force of the Construction Industry Institute. Although the machine's owner prefers to remain anonymous, a hearty thank you goes out for their spirit of international cooperation and their continued support.

5.3.1 Developer's Background

The construction company which developed the self-contained radio remote controlled power trowel is one of the world's largest construction contractors. Their stated business policy is to create a new era of construction using reliable high technology. They started investigating the application of robotics in construction in 1977 and developed the first successful robotic application for construction in 1982 with the prototype of a fireproof spraying robot.

Their Robotics Engineering Group (REG) is staffed with mechanical, electrical, and computer engineers who have developed for building construction not only a fireproof spraying robot, but also a multi-purpose travelling vehicle for concrete grinding and cleaning, a remote controlled steel beam assembly manipulator, a remote controlled steel beam flange clamp, a ceiling panel positioning robot, an exterior wall painting robot, and the remote controlled power trowel which is the subject of this study. Their REG also has developed robotic systems for tunnelling, nuclear reactor decommissioning, and manufacturing.

5.3.2 Development and Use of the Remote Controlled Power Trowel

Tasked with reducing the use of skilled hand finishers in the construction of concrete floors, the REG began examining the finishing process in 1986 and had a working prototype of the remote controlled power trowel by July of 1987. Eventually, seventeen units were produced, of which eleven are still in active use in Japan. The developer has used them on 110 job-sites on which over 5,000,000 sq ft of concrete has been troweled by the machines.

5.3.3 General Machine Description

The machine is self-contained, measures 7'-8" in diameter and 3'-0" tall when assembled and weights approx. 650 lbs. It utilizes a 5-hp gasoline engine to power three trowel heads, each of which has three 6 x 12 inch trowel blades. The trowel heads and machine frame revolve around the drive rollers as the machine operates. Also mounted to the machine's frame are a gasoline generator and electronic equipment which receive the radio signal from the hand-held remote, process the commands,

and power the drive rollers. The two drive rollers are independently driven by their own 24-volt electric motors and steer the machine across the slab. An aluminum safety cage is mounted over the machine and incorporates touch sensors and warning lights. The operator directs the direction, travel speed, and blade rotation speed through the accompanying hand-held remote which has ten push buttons, one of which is a shift key, giving the unit fourteen independent functions.

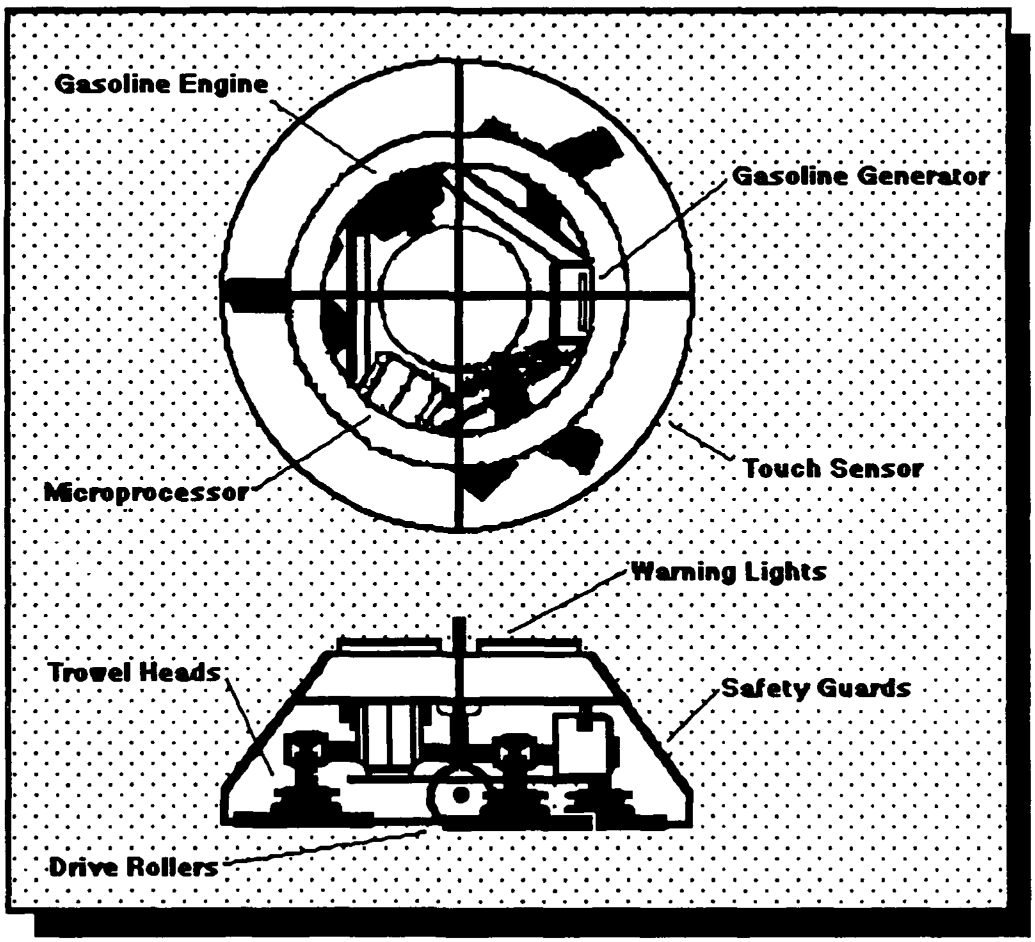


Figure 5.9 The Remote Controlled Power Trowel

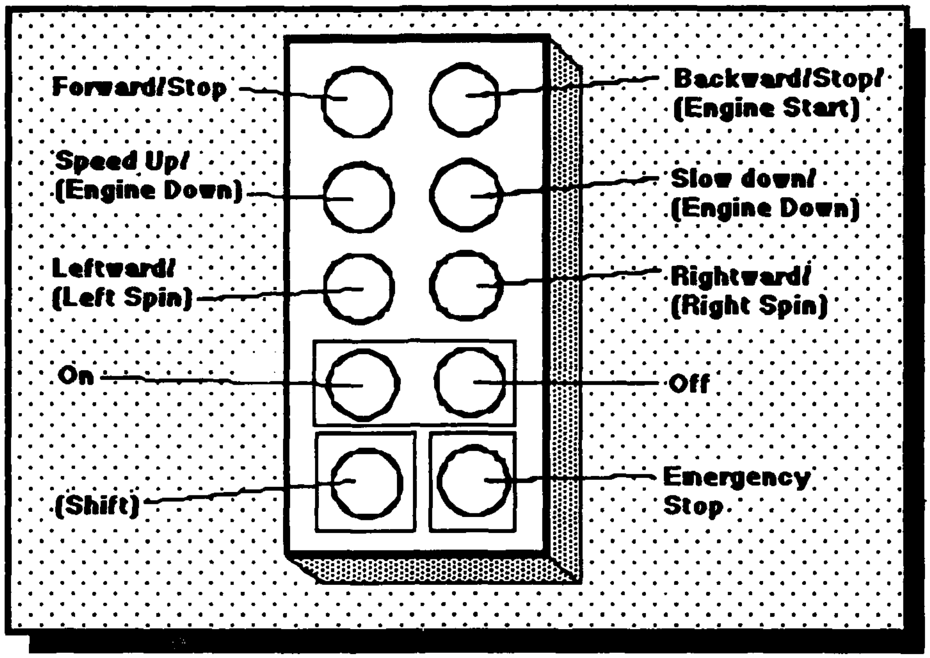


Figure 5.10 The Radio Remote Control

5.4 Critical Issues

All five of the major areas of concern identified in Chapter 4 need to be addressed in evaluating the remote controlled power trowel. Testing must examine how the machine will fit into the project environment in the U.S., how the machine performs as a concrete trowel, if it is economically justifiable, how it interacts with the operator, and finally how its use would impact business, labor, and society.

5.5 Scope and Limiting Factors

The time frame placed on the entire study by the ATS Task Force of CII was one year. During this time, the standard OT&E plan was developed, the remote controlled power trowel

was received and checked out, the unit was evaluated, and a final report was compiled.

The machine was based at The University of Texas at Austin, where laboratory testing, data analysis, and machine maintenance is to be performed. The selection criteria for field testing sites consided the transportation requirements from the machine's home base.

5.6 Test Objectives

There were four main test objectives:

1. Evaluate the overall effectiveness of the remote controlled power trowel, defining the bounds of its feasible use and examining how to expand those bounds through design or procedural changes.
2. Determine the appropriate level of automation for concrete floor finishing in the U. S. today.
3. Determine the potential for automation in concrete floor construction for tomorrow.
4. Evaluate the appropriateness of the Standard OT&E Plan.

5.7 Test Concept

Although it may be near a fully operational capacity inside of Japan, due to the lack of technical and spare parts support in the U. S., the remote controlled power trowel should be viewed as a prototype machine for the purposes of this evaluation. As such, testing should not be geared to only evaluate this specific machine as configured, but to examine the potential of the technologies which it represents.

When performing field tests, it makes sense to compare the machine directly against: 1.) the most common present method of task performance, and 2.) other machines which are available to earry out the task.

CHAPTER 6

TESTING OF THE REMOTE CONTROLLED POWER TROWEL

6.1 Introduction

To best meet the test objectives set forth in Section 5.6, testing of the remote controlled power trowel included controlled "laboratory" testing, fully integrated "field" testing, and in-depth study of the capabilities of competing methods.

The remote controlled power trowel was delivered to The University of Texas in April 1989 for the start of its one year evaluation period. A staff engineer from the machine's developer accompanied it to the University to explain its operation and train personnel it its use. In the first days of familiarization, difficulties were encountered with the transmitting frequency of the radio remote, but those were cleared up quickly, causing little impact to the schedule. It was planned to field test the machine at at least ten construction sites, ..owever, problems with the operation of the unit forced the cancellation of several of those planned tests. To compensate, some of the planned field testing was carried out at the University of Texas, and fortunately, the field testing actually performed yielded sufficient data to properly evaluate the device.

Physical testing and evaluation activities centered around head-to-head comparisons of the remote controlled power

trowel to walk-behind and ride-on trowels on the same slab under the same conditions. Independently, data was also collected on the operation of the remote, walk-behind, and ride-on trowels as well as concrete floor construction operations. Also, the remote controlled trowel was demonstrated to various equipment manufacturers, operators, and engineers, whose opinions were asked about the device's observed and potential performance . To round out the collection of evaluation information, available literature on the various competing systems was gathered and telephone interviews with various equipment manufacturers and concrete finishing contractors were conducted .

6.1.1 Testing Sites

In addition to projects under the control of the University of Texas, many active construction sites were offered by various CII member companies and firms engaged in concrete floor construction for the testing of the machine. Of all the sites available, six primary ones were eventually utilized:

SITE: Fujitsu Warehouse, Richardson, TX
FINISHING CONTRACTOR: Terry J. Fricks, Inc.
PROJECT DESCRIPTION: 200,000 SF Warehouse
90,000 SF Office on 3 floors
ACTIVITIES PERFORMED: Machine Field Testing
Collection of Field Data

SITE: J.C. Penney Store, Lewisville, TX
FINISHING CONTRACTOR: Fellers Concrete
PROJECT DESCRIPTION: 70,000 SF Slab on Grade
ACTIVITIES PERFORMED: Collection of Field Data

SITE: Sherwin-Williams Warehouse, Waco, TX
FINISHING CONTRACTOR: Williams Concrete
PROJECT DESCRIPTION: 800,00 SF Warehouse Floor
ACTIVITIES PERFORMED: Collection of Field Data

SITE: UT Balcones Research Center, UT-Austin, TX
ACTIVITIES PERFORMED: Machine Lab Testing
Machine Demonstrations

SITE: UT Micro Electronics Lab, UT-Austin, TX
GENERAL CONTRACTOR: Clearwater Construction
ACTIVITIES PERFORMED: Collection of Field Data

SITE: UT Sports Center, UT-Austin, TX
GENERAL CONTRACTOR: Pepper-Lawson
ACTIVITIES PERFORMED: Machine Field Testing
Collection of Field Data
Machine Demonstrations

6.1.2 Testing Time-Line

Some highlights of testing and evaluation activities which have taken place to date are:

4/11/89 - Machine delivered to UT.

4/13/89 to 5/22/89 - Performed machine field testing at the UT Sports Center Job Site. Troweled a total of 6000 sq ft of concrete (roof slab, slab on grade) on three separate days. Demonstrated to several different groups of contractor personnel. Studied concrete placement and finishing operations. Experienced some transmitter frequency problems in early stages which were quickly solved.

6/2/89 to 6/9/89 - Demonstrated to the participants of the 6th International Symposium on Automation and Robotics in Construction held in San Francisco, CA.

6/16/89 to 7/26/89 - Machine system evaluations performed at the Balcones Research Center.

7/27/89 to 9/13/89 - Machine drive rollers were found to be inoperable during a routine check-out. They were unable to be repaired at The University, but the problem was found to be in the machine's controller. The controller was shipped back to Japan for repairs.

8/28/89 to 9/1/89 - Field data collection at J.C. Penny store site. Remote controlled trowel originally scheduled for use here, however, operability problems forced its cancellation.

9/14/89 to 2/6/90 - After the return of the repaired controller from Japan, machine testing resumed at Balcones Research Center. Some of the planned field tests were shifted to this site. Also, the machine was demonstrated to equipment manufacturer personnel.

9/21/89 to 9/25/90 - Field data collection at the University of Texas Micro Electronics Lab site. Focus was concrete placement operations.

10/16/89 to 10/20/89 -Field data collection at Sherwin-Williams warehouse site. In depth study of the use of riding trowels.

2/7/90 - Tested at Fujitsu Warehouse Job Site on 500 sq ft casting slab. Right drive roller became inoperable during testing. No further tests were performed after this date.

6.2 Project Environment Interaction

The first of the five major areas of concern for evaluation is the new device's ability to interact with the existing project environment. As presented in Section 4.1.1, here all aspects of the present task performance are examined, impacts of the automated device on project management and design & procurement are assessed, and any unique problems posed by a failure of the new device are determined.

6.2.1 Task Analysis

Task analysis looks at what, where, why, how, when, and by who the work is presently being performed in an effort to understand how the automated device can function under the same conditions and how those conditions can be modified to optimize the automated device's performance.

Physical Layout - Power troweling requires a certain minimum placement area to be cost effective, with walk-behind trowels used on anything over a few hundred square feet and ride-ons not used unless there are a few thousand square feet to finish. The remote controlled power trowel is used by its developer only on warehouse floors and office building slabs. Such large slabs on grade are usually in open areas exposed to wind, rain, dust, and variable sunlight, while the elevated office building slabs have associated with them a congestion of formwork and competing trades as well as limited access to the immediate work. Figures 6.1 and 6.2 show the typical conditions encountered under both types of work.

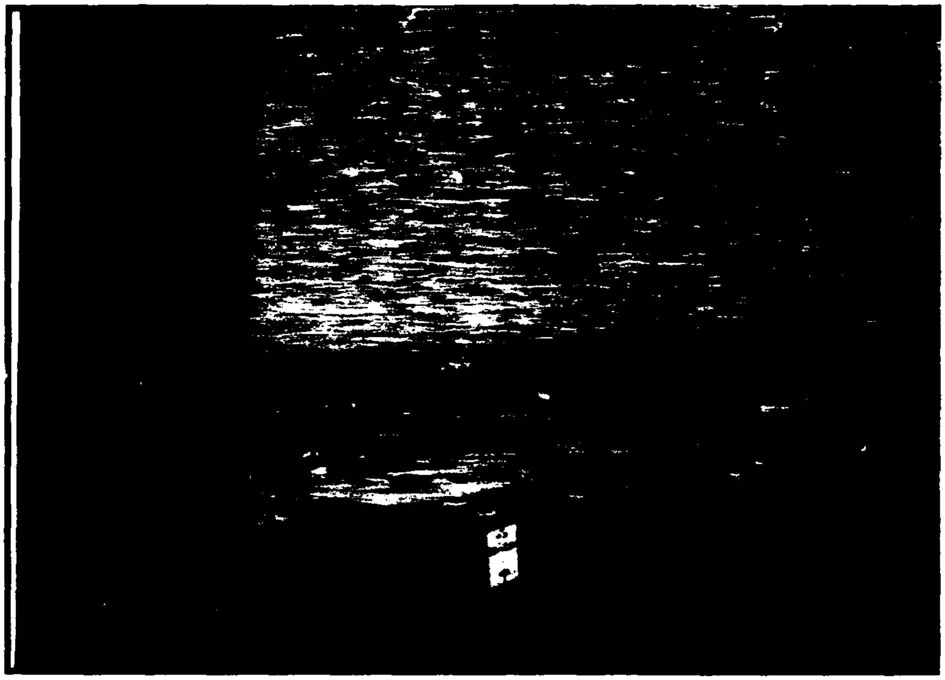


Figure 6.1 Typical Slab on Grade Site Conditions

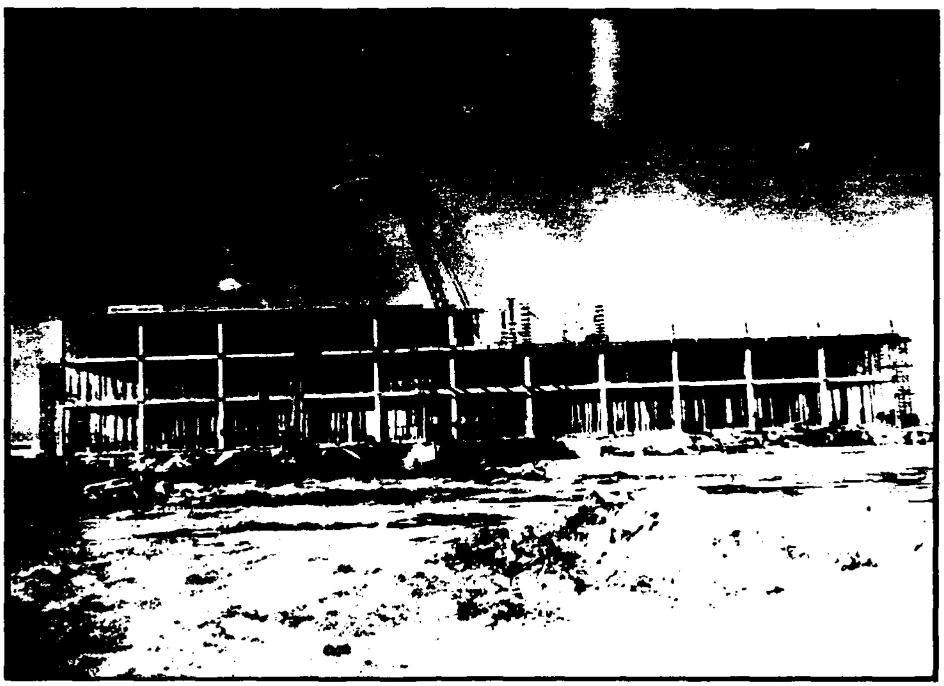


Figure 6.2 Typical Elevated Slab Site Conditions

Seasonallity & Variability of Work - In the north, the colder climate causes lay-offs in Winter months, while in much of the south, the Winter season's weather is unpredictable and causes slow-downs in production of concrete placement. Furthermore, each slab is different due to its unique shape, location, and work crew, while conditions across the slab are highly variable due to differences in curing conditions, obstructions, mix from truck to truck, and pouring pattern.

Figure 6.3 Hand Troweling

Impact of Weather - Rain and freezing temperatures will stop work entirely. Wind, sun, light rain, and temperature changes all effect the curing rates of the concrete across the slab.

Present Methods & Materials - Presently, steel troweling of floors in the U.S. can be accomplished by hand or with the use of walk-behind or ride-on power trowels (See Figures 6.3 to 6.5). Because of their heavier weight, ride-ons cannot be placed on

the slab the same time as a walk-behind, thus, walk-behinds are the machine of choice for power floating. In fact, the inventor of ride-ons, Butch Holtz suggests always to use a walk-behind with float shoes for initial machine floating prior to the use of a ride-on trowel. Sometimes, since contractors must keep workers which they have employed for the entire day busy after the intensive placement operations are complete, they will not use their labor saving ride-on trowel, but instead use only their less efficient walk-behinds for troweling and will hold the great production capacity of their ride-on in reserve to catch up if the slab stiffens faster than the walk-behinds can trowel it.

Figure 6.4 Walk-Behind Troweling

In addition to these mechanized methods, there are four different automated trowels under development by Japanese construction companies. Figures 6.6 to 6.9 show examples of each of these devices.

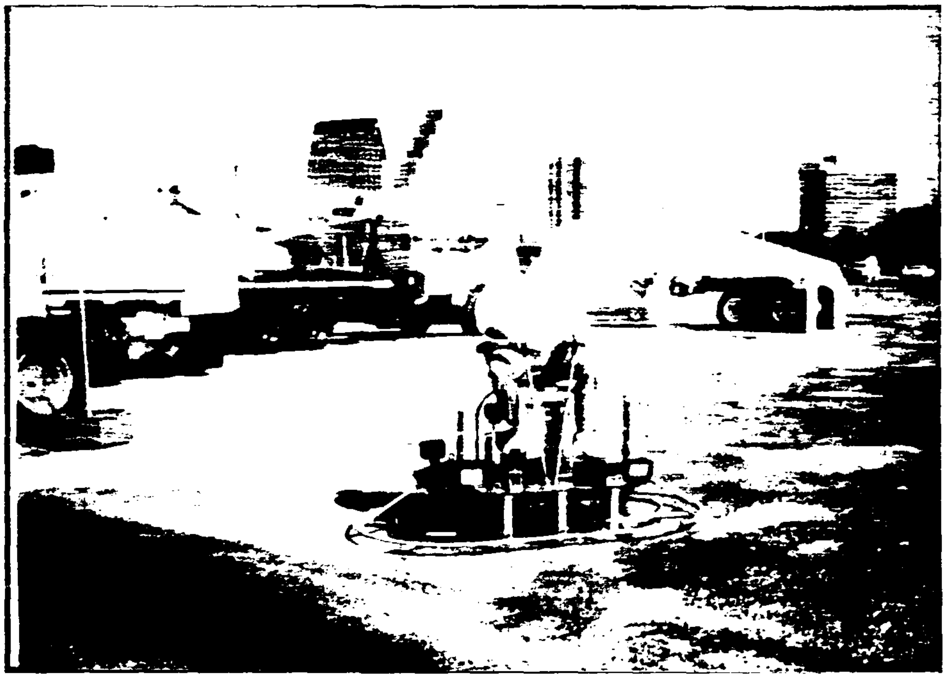


Figure 6.5 Ride-On Troweling

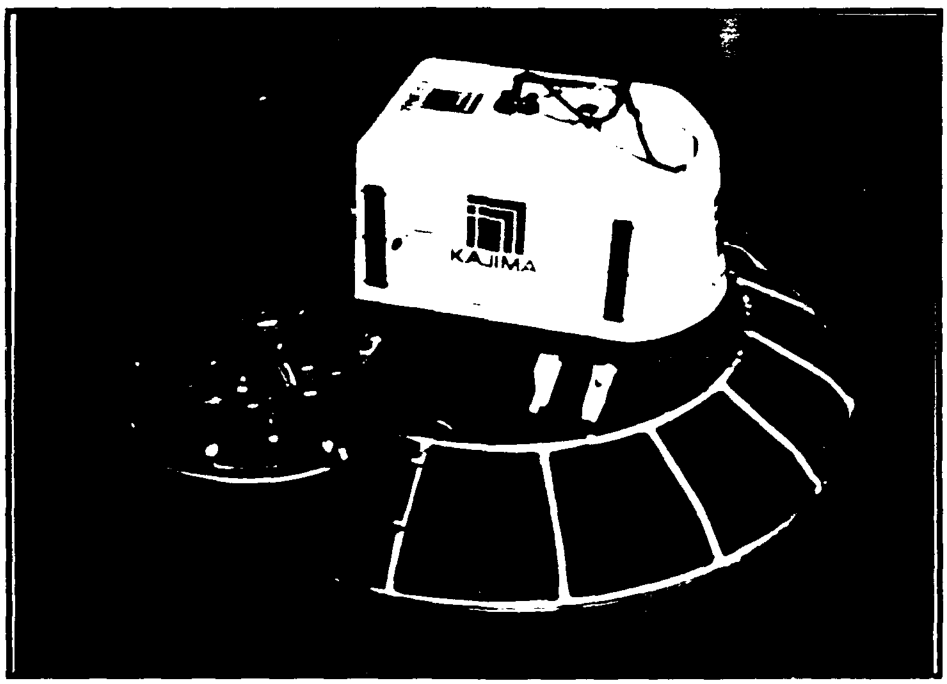


Figure 6.6 Kajima's Automated Trowel

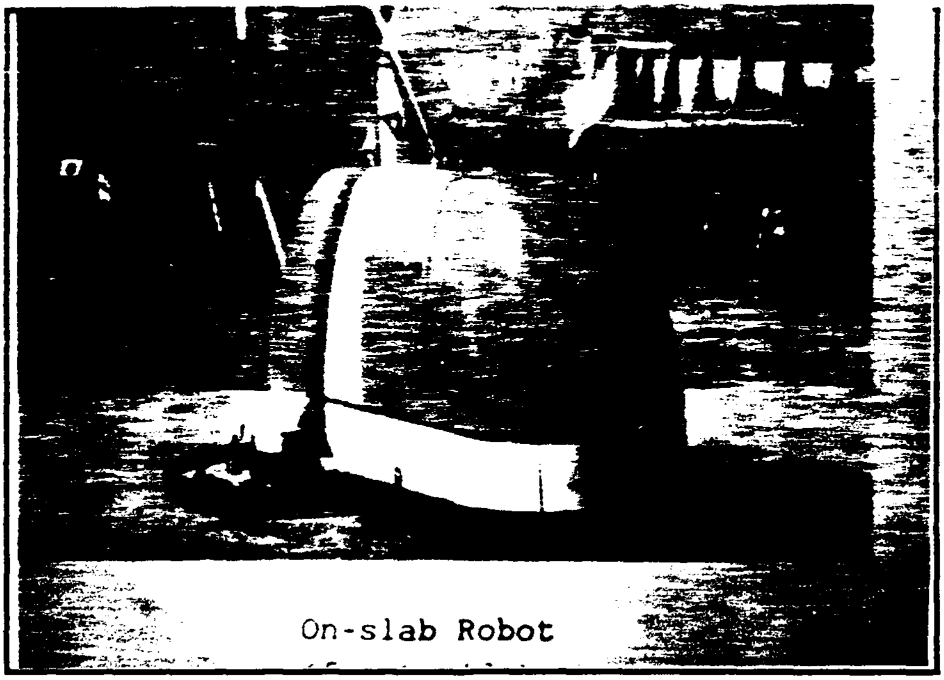


Figure 6.7 Ohbayashi's Automated Trowel

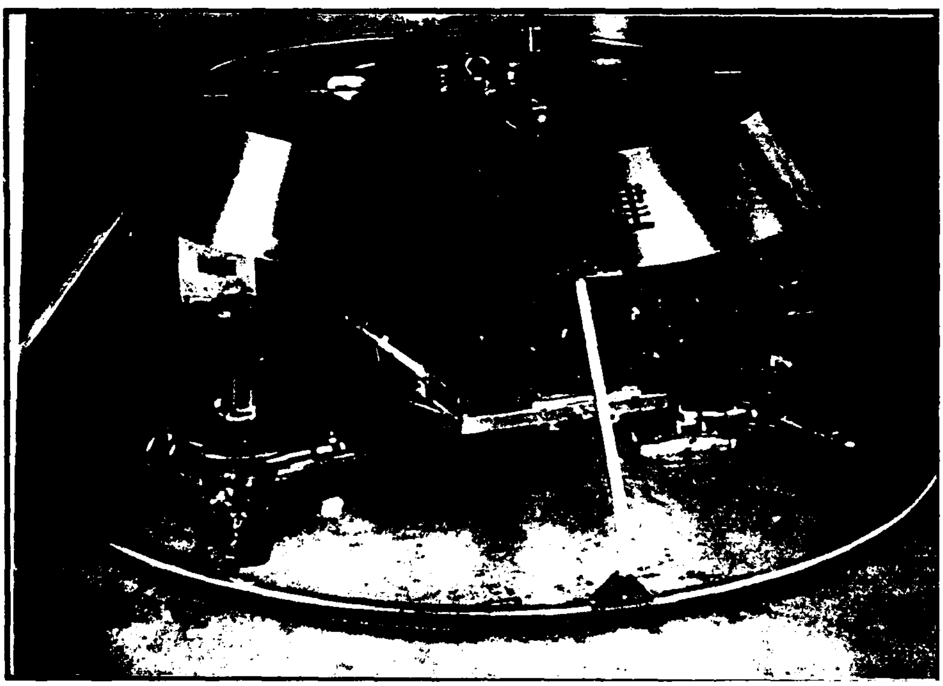


Figure 6.8 Shimizu's Automated Trowel

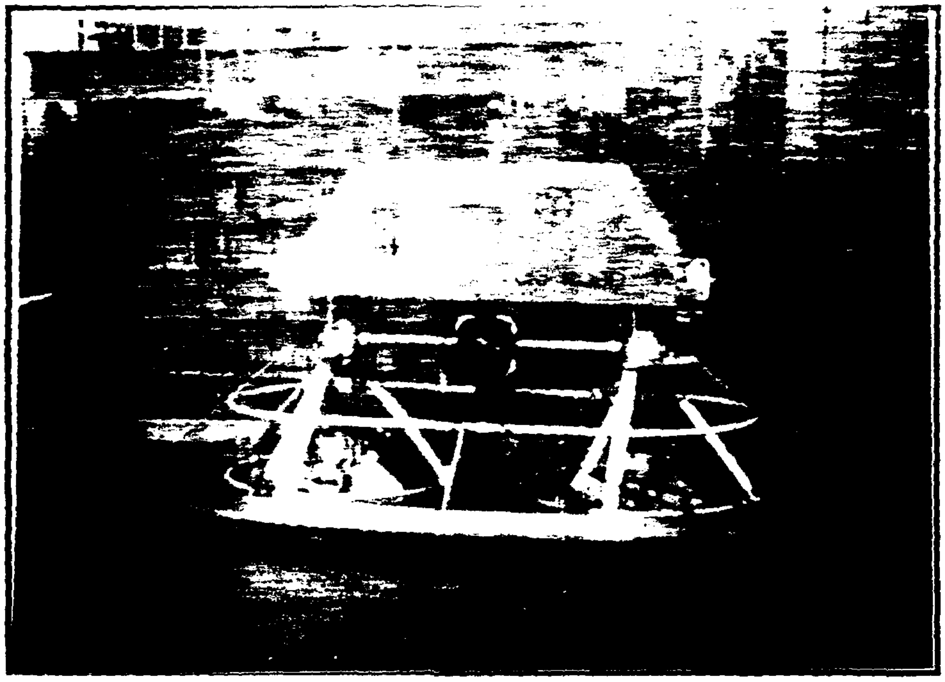


Figure 6.9 Takenaka's Automated Trowel

The ride-on power trowel is currently the most advanced form of troweling machine in the U. S. For this reason, the characteristics of all the available ride-on trowels and all of the competing automated trowels were examined to determine the relative capabilities of the remote controlled power trowel. Table 6.1 is a comparison of the available ride-on trowels and Table 6.2 is a comparison of the competing automated trowels.

Table 6.1 Ride-On Power Trowels

MANUFACTURER	ALLEN ENGINEERING P.O. Box 1525 Euless, TX 76039 800-643-0095	ARROW-MASTER 1201 Seventh St E. Moline, Ill 61244 800-433-7185	BARTEL 56 Harvester Ave. Batavia, NY 14020 800-247-8577	BESTO 4901 Dwight Evans Rd Charlotte, NC 28217 800-552-8261	WHITEMAN MULTIQUIP INC. PO Box 6254 Carson, CA 90749 800-421-1244
MACHINE TYPE	Double Ride-On	Double Ride-On	Double Ride-On	Double Ride-On	Double Ride-On
MODEL	436-2(Note 1)	RO2-18(Note 2)	BTR 72(Note 3)	B446-2(Note 4)	JRT-36V(Note 5)
FINISHING BLADES AVAILABLE	Float, Finish Combination	Float, Finish Combination	Float, Finish Combination	Float, Finish Combination	Float, Finish Combination
OPERATIONS PERFORMED	Float & Finish	Float & Finish	Float & Finish	Float & Finish	Float & Finish
CONTROL METHOD	Twin Levers	Single Stick	Single Stick	Twin Levers	Twin Levers
DEVELOPMENT STARTED	1986	1972	1986	1989	1986
FIRST SOLD	1986	1972	1987		1989
NUMBER SOLD	300	3000	15	0	225
COST PER UNIT	$7,000	$7,000	$6,990	$7,000	$7,000
MINIMUM JOB SIZE	10,000 sf/day		10,000 sf/day		1,000 sf/day
DIMENSIONS	71 x 40 x 50 in	87 x 45 x 48 in	66 x 36 x 48 in	74 x 41 x 50 in	73 x 39 x 46 in
WEIGHT	690 lbs	725 lbs	575 lbs	606 lbs	318 lbs
MAX TRAVEL SPEED	300 ft/min	500 ft/min	500 ft/min	?	500 ft/min
MAX BLADE ROTATION	110 rpm	120 rpm	110 rpm	110 rpm	150 rpm
SINGLE PASS COVERAGE (Note 6)	105,000 sf/hr	212,000 sf/hr	165,000 sf/hr	?	216,000 sf.hr
FINISHING COVERAGE	15,000 sf/day	15,000 sf/day	15,000 sf/day	?	9,000 sf/day

Note 1 - Allen Engineering manufactures 3 different double ride-on models.
Note 2 - Arrow-Master manufacture 4 different double ride-on models and 2 different tripple ride-on models.
Note 3 - Bartel manufactures 3 different double ride-on models.
Note 4 - Besto is the newest liscensee to manufacture and sell ride-on trowels in the United States.
Note 5 - Whiteman manufacture six different double ride-on models, including one light weight 318 lb model.
Note 6 - Single Pass Coverage equalsMax Travel Speed multiplied by Machine Width.

Table 6.2 Automated Power Trowels[35]

MANUFACTURER	KAJIMA Tokyo, Japan	OHBAYASHI Tokyo , Japan 03-292-1111	SHIMIZU Tokyo , Japan 03-535-4111	TAKENAKA Tokyo, Japan 03-542-7100
MACHINE TYPE	Supervised Programmable	Autonomous Programmable	Radio Remote Controlled	Radio Remote Controlled
TRADE NAME	MARK II		FLATKN	SURF ROBO
OPERATIONS PERFORMED	Troweling Only	Troweling Only	Troweling Only	Troweling Only
CONTROL METHOD	Self Contained, Gyro-Compass & Touch Sensor Navigation, Electric Motors	Self Contained, Obstacle Avoiding Laser Navigation, Gas Engine Powers Electric Motors	Self Contained, Keyed Commands, Gas Engines drive Blades and Power Electric Rollers	Tethered Power Cable, Keyed Commands, Electric Motors
DEVELOPMENT STARTED	1986	1986	1986	1986
WORKING PROTOTYPE	March 1986	October 1987	July 1987	December 1986
DEVELOPMENT MOTIVATION	Reduce Hand Labor	Reduce Hand Labor	Reduce Hand Labor	Reduce Hand Labor
DIMENSIONS	4.6 x 3.9 x 2.2 ft (1.4 x 1.2 x 0.67 m)	5.1 x 6.5 x 3.6 ft (1.6 x 2.0 x 1.10 m)	7.6 x 7.6 x 2.7 ft (2.3 x 2.3 x 0.8 m)	7.2 x 3.9 x 3.6 ft (2.2 x 1.2 x 1.1 m)
WEIGHT	440 lbs (200kg)	662 lbs (300 kg)	662 lbs (300 kg)	440 lbs (200 kg)
MAX TRAVEL SPEED	59.0 ft/min (18 m/min)	36.1 ft/min (11 m/min)	33.5 ft/min (10.2 m/min)	39.4 ft/min (12 m/min)
BLADE ROTATIONAL SPEED			100 rpm	35 rpm
MAX THEORETICAL SINGLE PASS COVERAGE	11,625 sq ft/hr (1,080 sq m/hr)	11,047 sq ft/hr (1025 sq m/hr)	15,155 sq ft/hr (1400 sq m/hr)	17,050 sq ft/hr (1,584 sq m/hr)
FINISHING COVERAGE	3,000 sf/day (280 m/day)	3,000 sf/day (280 m/day)	3,000 sf/day (280 m/day)	3,000 sf/day (280 m/day)

Although there are 19 different ride-on trowel models currently manufactured in the U. S. and they range in size and configuration from a 318 lb double trowel to an 800 lb triple trowel, the trend in the market seems to be a 600-700 lb double trowel. An aggregate of the five double trowels presented in Table 6.1 shows us that the modern ride-on trowel had its development start in 1986, is a 77-in x 40-in x 48-in, 650 lb double trowel, is controlled by twin hand levers and is capable of floating and finishing. These ride-on trowels cost about $7000.00 and have a production rate of about 15,000 SF/day.

Looking at the four automated trowels presented in Table 6.2, it can be seen that their development also started in 1986, that they are about 72-in x 66-in x 36-in and range in weight from 440-660 lbs. Three of the four require the full time attention of an operator, while the fourth still requires an individual dedicated to the machine while it is in use. Their estimated purchase prices start at $40,000.00 and go upward and their average production rates are 3000 SF per day.

Present Production Rates - Actual production rates are dependent upon many factors including: operator experience & efficiency, concrete mix and consequent setting, weather, environment, etc. The record for the most concrete troweled by a single man in one day is 38,000 sq ft, this being performed by a modified triple ride-on trowel[36]. The following figures are a compilation of manufacturer, operator, contractor, and engineer comments, observations, and various published sources.

Hand:	300	-	600	SF/day
Walk-Behind:	1,500	-	3,000	SF/day
Ride-On:	7,500	-	15,000	SF/day
Automated:	1,500	-	3,000	SF/day

Present Labor & Specs - According to the various ride-on manufacturers, the typical finishing contractor does under $500K in annual business and has under 10 permanent employees. Less than 100 contractors nationwide perform over $5M in annual business and employ over 50 permanent employees. Finishers, though highly skilled, are generally poorly paid, typically aren't native English speaking and have less than a high school education.

Specifications are quantitative when calling out mix designs, but are generally less specific and qualitative on describing desired finishing. The ACI Floor Classification System is the standard for calling out required finishes and the ASTM F-Number system is becoming the standard for specifying floor flatness and levelness. Some specifications still limit the finisher's production options by either specifically calling for "a hand trowelled" or "machine trowelled" finish.

6.2.2 Impact on Project Management

Material Supply, Schedule, Work Element Integration, and Controls & Data Acquisition are relatively unaffected by the choice of troweling method. Since troweling involves no actual addition of mass to the structure, there is no change in material supply. The actual task performance of concrete floor troweling is driven by the setting of the concrete, therefore work start times, task duration, and completion time are unaffected. Due to the possibility of signal interference, the use of the radio remote control does require slightly more pre-planning over other methods.

6.2.3 Impact on Design & Procurement

Since the radio remote controlled power trowel is only used for the final troweling of the slab, its use has no impact on the timing or format of the design, drawing, or specifications. Because the machine works best on large, open area pours, the troweling operation can be made more efficient by the minimization of obstructions or elevation changes in the slab design.

6.2.4 Impact of Possible Failure

The remote controlled trowel brings no unique constraints due to its failure modes to the job-site. Back-ups in case of failure must be provided for in the same manner as for a ride-on trowel.

6.3 System Performance

The second major area of evaluation, as detailed in Section 4.1.2, examines the abilities of the automated device to integrate into the present work environment. The thrust of this area is to determine how the machine physically performs its intended tasks and how the individual components of the device work together as a whole.

6.3.1 Production Rate

Testing at The University of Texas indicates that the maximum travel speed of the machine is 26.5 ft/min. Multiplying this transverse speed by the machine's diameter of 7'2'", gets a maximum theoretical single pass coverage rate of 11,400 SF/hr compared to a maximum single pass coverage for a double ride-on trowel of over 100,000 SF/hr. This implies that

the ride-on trowel has a ten-to-one advantage in production over the remote controlled trowel.

To get a better grasp on the true production capacities of the devices, field testing was performed at various sites matching the remote controlled power trowel against both ride-on and walk-behind trowels. Figures 6.10 and 6.11 depict this testing. Taking into account curing rates, machine acceleration, deceleration, turns, overlap, and an average of three separate trowing passes with a 20 to 30 minute delay between each, the remote controlled trowel has the capacity to finish between 1500-3000 square feet of concrete per day, making it roughly equivalent in production capacity to a walk-behind trowel. By comparison, the ride-on trowels can finish roughly five times as much concrete flooring.

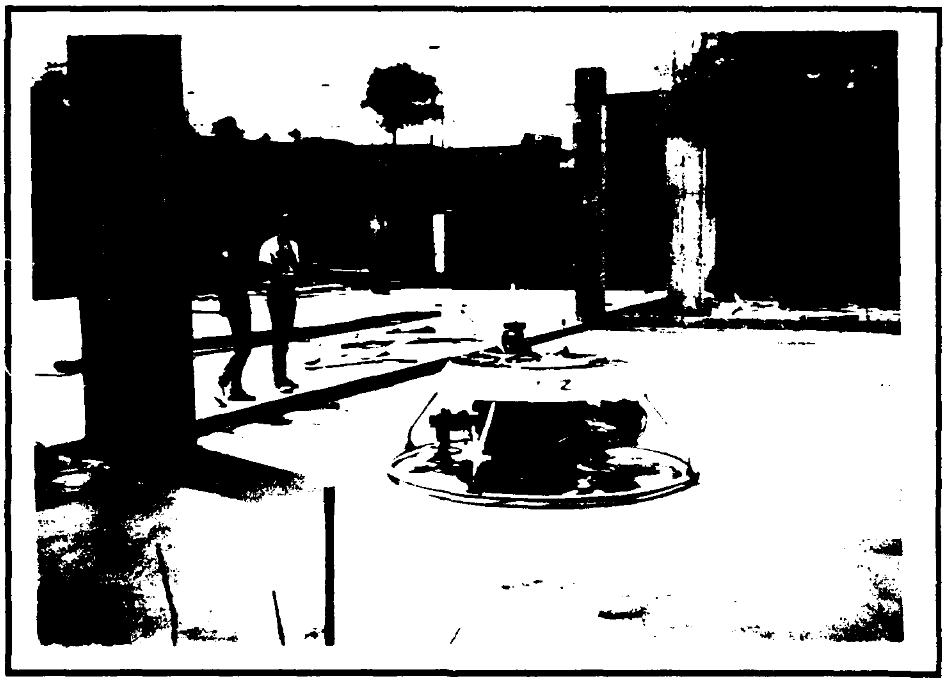


Figure 6.10 Field Testing of the Remote Trowel

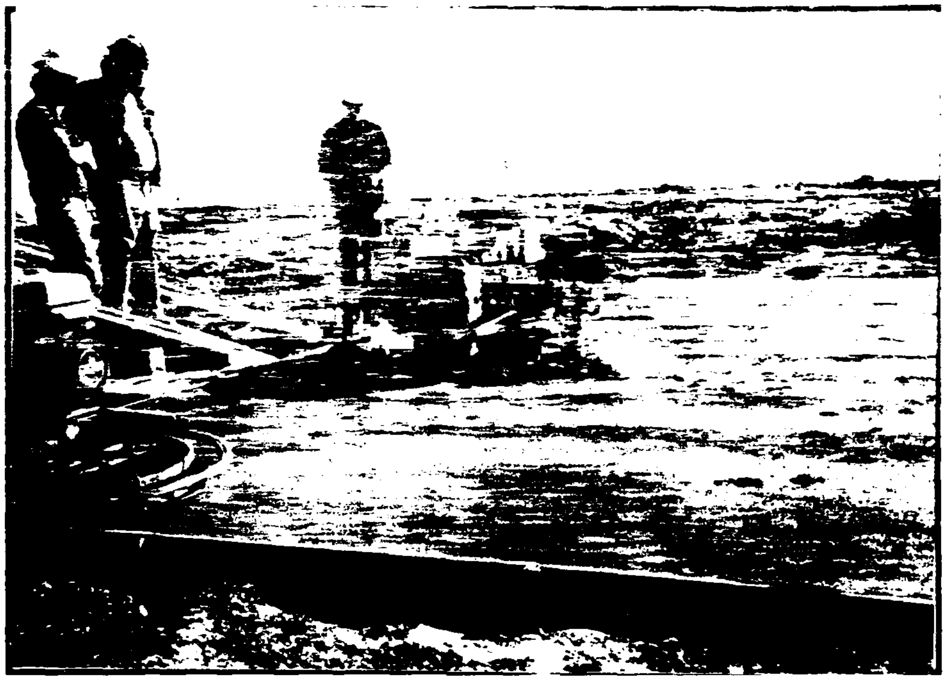


Figure 6.11 Field Testing of the Remote Trowel

6.3.2 Quality

Required Level of Quality - Quality in concrete floors takes on several very different measures. First, there is the strength of the concrete in compression and flexure, which is largely dictated by the mix design. Then, there is the consistency of the concrete throughout the slab, which is dictated by the sub-grade preparation, the placement methods, and the consolidation techniques. Some floors may specify a required level of hardness, which is influenced by the amount of troweling performed and the use of dry shake hardeners. Finally, there is the smoothness or the flatness and levelness of the finished floor which are influenced by the forming, strike-off, and finishing operations. Of these various measures of quality, troweling

operations only impact the hardness, flatness and levelness of the final floor.

Hardness - Hardness is a measure of the floor's ability to provide adequate traffic wear resistance, to absorb impact, and to be sufficiently dense to resist spills. Achieved hardness can be measured by a penetrometer, but is usually specified by the number of troweling passes or the inclusion of specific amounts of hardening compounds.

Some ride-on trowel manufacturers claim that increased hardness is dependent upon machine weight and the rotational speed of the blades. To some degree, this was found to be true. Faster blade rotation allows the trowel to operate at an increased blade angle of attack. Along with the machine weight, this allows a greater blade force to be exerted on the concrete. This greater force means that troweling operations can have a positive effect on the concrete further into its set-up, thus increasing the final hardness of the floor. Since most walk-behind, ride-on, and automated trowels operate at roughly the same maximum blade rotational speed,100-120 rpm, then machine weight is the only differentiating characteristic between them when examining floor hardness.

Walk-behinds exert a maximum blade force of roughly 0.4 psi, while most ride-ons and the remote controlled trowel exert a maximum blade force of 1.0 psi. Thus, the remote controlled trowel can achieve a floor hardness greater than walk-behind trowels and equal to a ride-on trowel. However, final floor hardness can be increased eight times over that of a well troweled surface by the incorporation of shake-on hardeners into the top 1/8-inch of the slab[37], thus overshadowing any benefits the ride-ons and remote controlled trowel have.

Flatness - Specifications historically called for a flatness variance of 1/8 inch in 10 feet. But this method fails to specify the number of waves within the 10 foot distance that a floor can possess. It could gently slope to a low point in the center or it could have many small waves in a pattern similar to a washboard. Today's "good" specs are now referencing two numbers, F_F and F_L, which are indicators of the floor's flatness and levelness respectively. The higher the number, the flatter the floor. ASTM E1155, Standard Test Method for Determining Floor Flatness and Levelness Using the F-Number System, uses floor curvature over a 24-inch distance as a measure of flatness, and floor slope over a distance of 10 feet as a measure of levelness[39]. These measures of flatness and levelness are usually specified at two different values, one measuring the overall slab, and one measuring any given local area of the slab. For most floors constructed under the old 1/8-inch in 10 feet spec, the F_F and F_L usually fall between 15 and 45. Today, for some warehouse construction, specifications call for an overall F_F of 100 and an overall F_L of 50, these floors are considered to be superflat and are four times flatter than those constructed under the old specification. Table 6.3 shows how conventional and superflat floors compare.

RECOMMENDED F-NUMBERS FOR DIFFERENT FLOOR CATEGORIES				
Floor Category	Minimum F_F and F_L number			
	Overall		Local	
	F_F	F_L	F_F	F_L
Conventional				
Bullfloated	15	13	13	10
Straightedged	20	15	15	10
Flat	30	20	15	10
Very Flat	50	30	25	15
Superflat	100	50	---	---

Table 6.3 Recommended F-Numbers for Different Floors[38]

The flattest and levelest floors are those constructed under superflat specifications, having an overall F_F of 100 and an overall F_L of 50. Terry J. Fricks, Inc. out of Fort Worth, Texas, specializes in superflat construction and is credited with creating the world's flattest floor, an overall F_F of 150, when constructing a parts distribution center for Freightliner in Reno, Nevada in early 1989.[40] The Fricks organization feels that the choice of troweling machine makes no difference in the final flatness and

Figure 6.12 Highway Straightedge Use in Superflat

levelness of a floor, that levelness of a slab relates primarily to the accuracy in setting of forms and the straightness of the stike-off tool, while the key to flatness is the timing and number of restaightening operations. On superflat, they use a highway straightedge in lieu of a bull float, and restaighten the surface between each floating and troweling pass with that straightedge. This operation is shown in Figure 6.12. In discussions with equipment manufacturers, such as Allen Engineering Corp out of

Euless, Texas, they supported the notion that troweling machines have minor impact on flatness and levelness as compared to fromwork, screeds, and straightedges. Allen promotes the use of metal forms with milled top edges, vibratory screeds, and highway staightedges to contractors performing superflat work.

6.3.3 Operability

The remote controlled power trowel effectively can only trowel, since it cannot be fitted with float shoes because the machine's drive rollers would sink into the unstiffened paste anyway. The initial use time of the machine is about 30 minutes later than that of a walk-behind trowel or 4.5 hours after batching for a 78°F day. It can not trowel within 1 foot of obstructions nor within 2 feet of elevated slab edges. Here, hand troweling must be used. The recommended overlap from one traverse to the next is 9 in. The remote controlled trowel can run 3-4 hours between gas fill-ups and the hand held transmitter must be charged for 8 hrs after each day of use.

The operating envelope of the remote controlled trowel is slightly less than the ride-on trowel, which is also capable of limited floating operations and can be used closer to obstructions.

6.3.4 Reliability & Durability

The radio remote controlled power trowel, pictured in Figure 6.13, has two major sub-systems which must be assessed: one mechanical and one electrical. The mechanical system drives the rotation of the trowel blades, while the electrical system powers the drive rollers and control electronics.

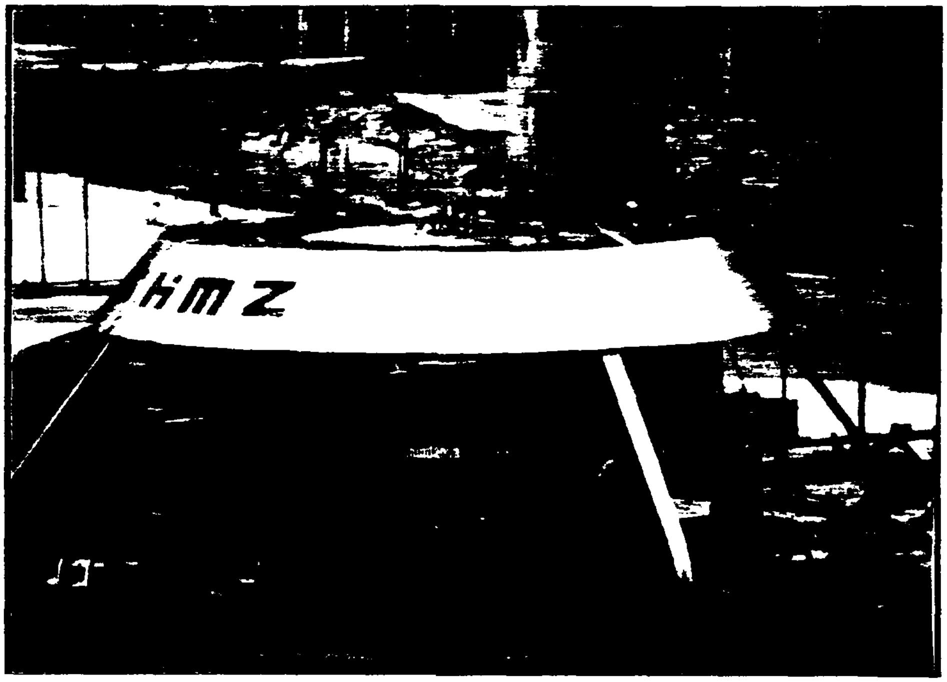


Figure 6.13 The Assembled Machine

Mechanical Sub-system - (Figures 6.14-6.16) A Robin 5HP gasoline engine manufactured by Fuji Heavy Industries supplies the power for the trowel blades. Power is transferred to the trowel heads by a three-way bevel gear box. Between the motor and the bevel gear box is a centrifugal clutch. The trowel heads utilize worm gears to transfer the rotation of the individual drive shafts into the plane of the trowel blades.

Electrical Sub-system - (Figures 6.17-6.18) A Shindaiwa gasoline generator supplies both AC and DC current for the remote controlled power trowel. The machine's drive rollers are powered by individual 24 volt DC motors which are energized by a car battery and the generator connected in series. Themachine's control electronics operate off of the generator's 60 hz, 100 volt AC output.

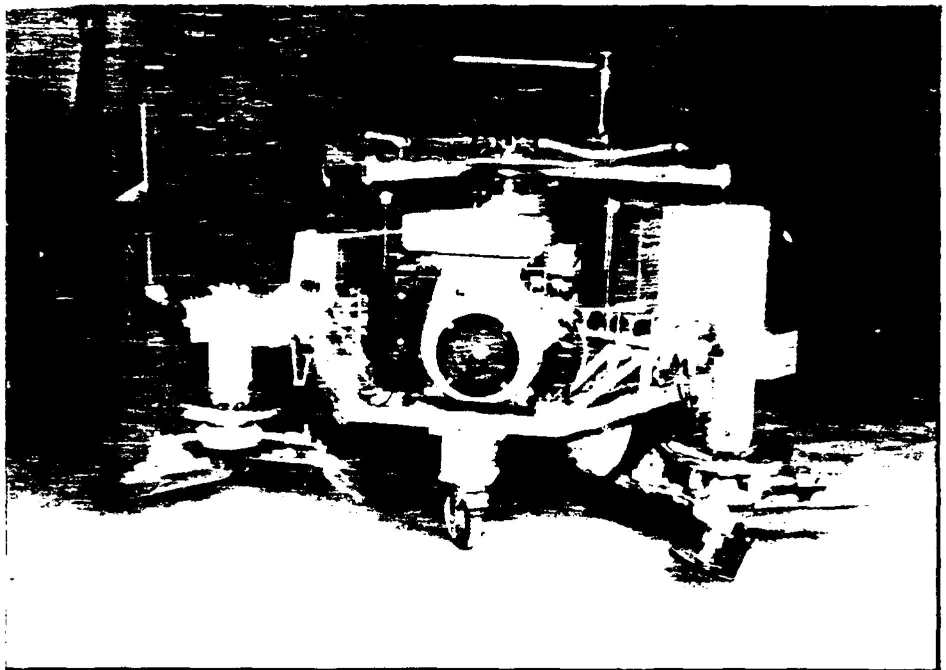


Figure 6.14 The Gasoline Engine

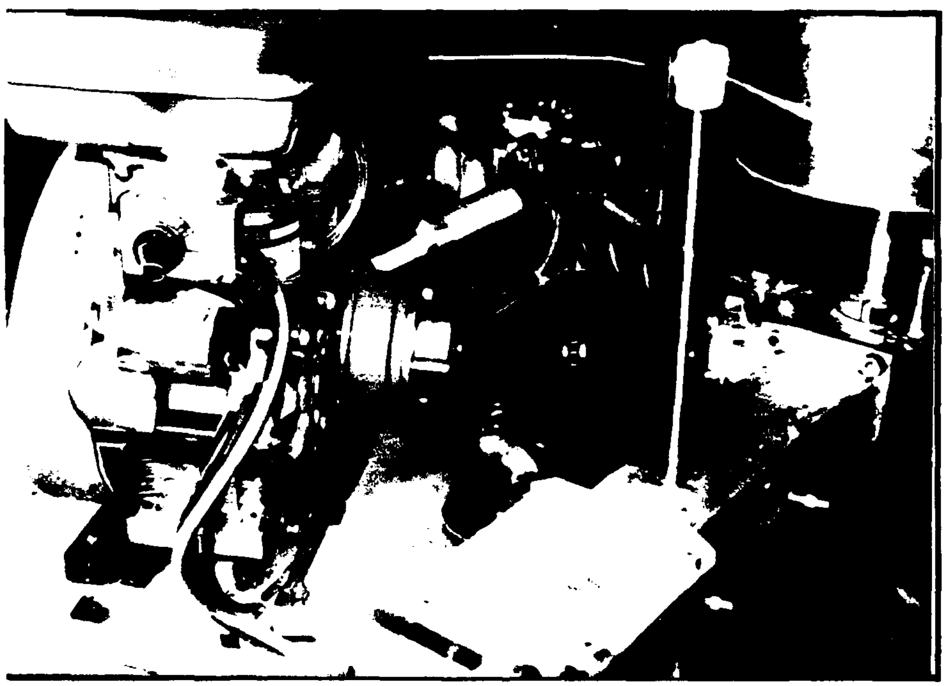


Figure 6.15 The Centrifugal Clutch

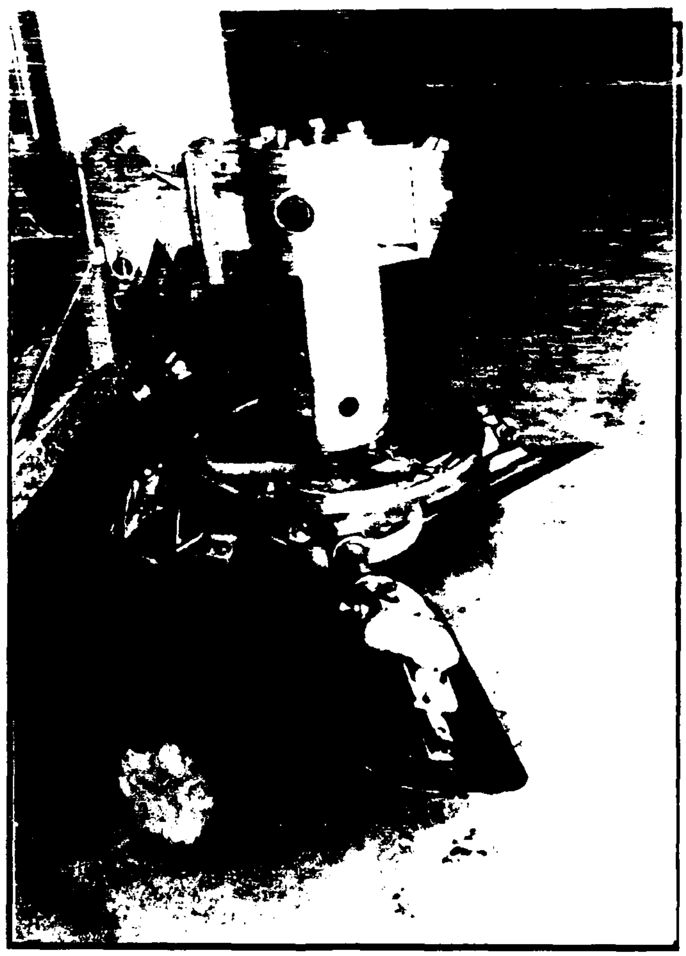


Figure 6.16 The Trowel Head

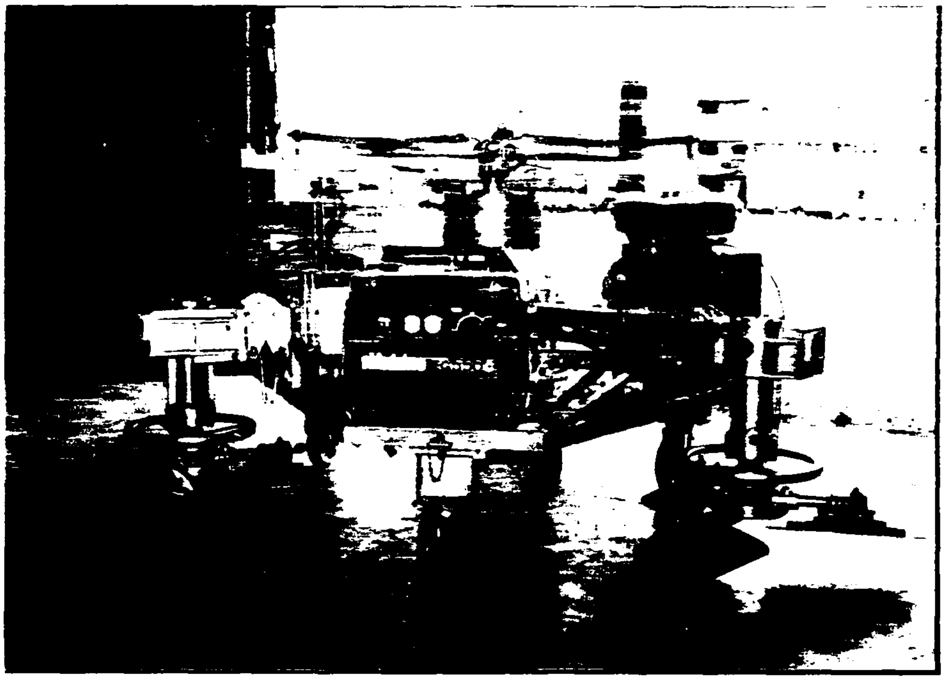


Figure 6.17 The Gasoline Generator

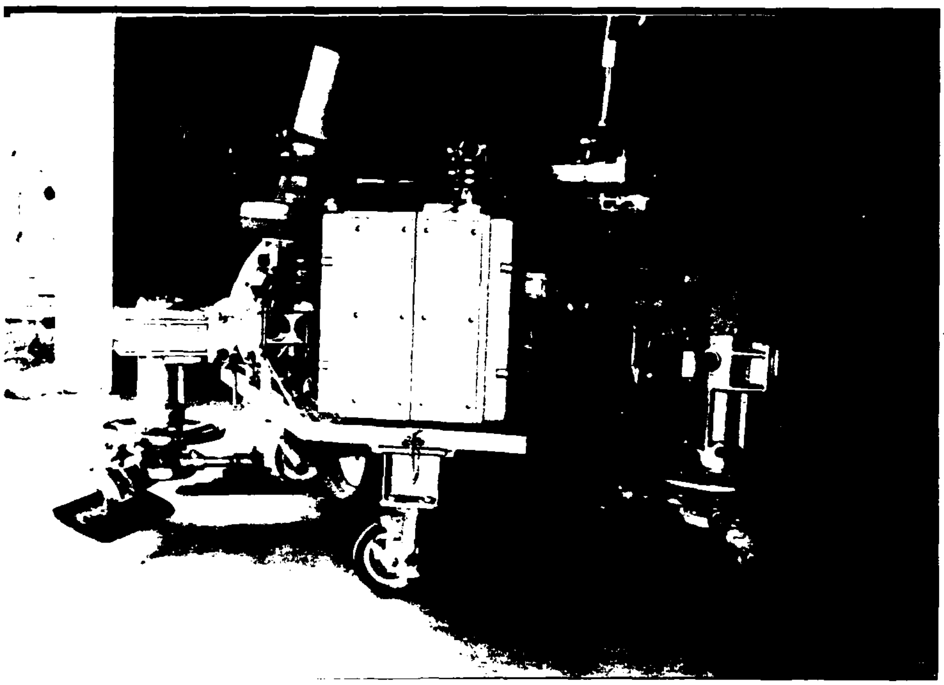


Figure 6.18 The Controller Unit

Electronics - (Figures 6.19-6.21) The hand held radio remote transmits 1000 BPS over a 68-90 MHz FM signal. The receiver decodes the transmission signal and trips relays which in turn send on/off messages over sixteen channels to the controller's microprocessor. The microprocessor interprets these inputs and sends the proper on/off message to eight relays which control the power to the machine's drive rollers, the engine throttle, and the warning lights, directing each to perform the desired operation.

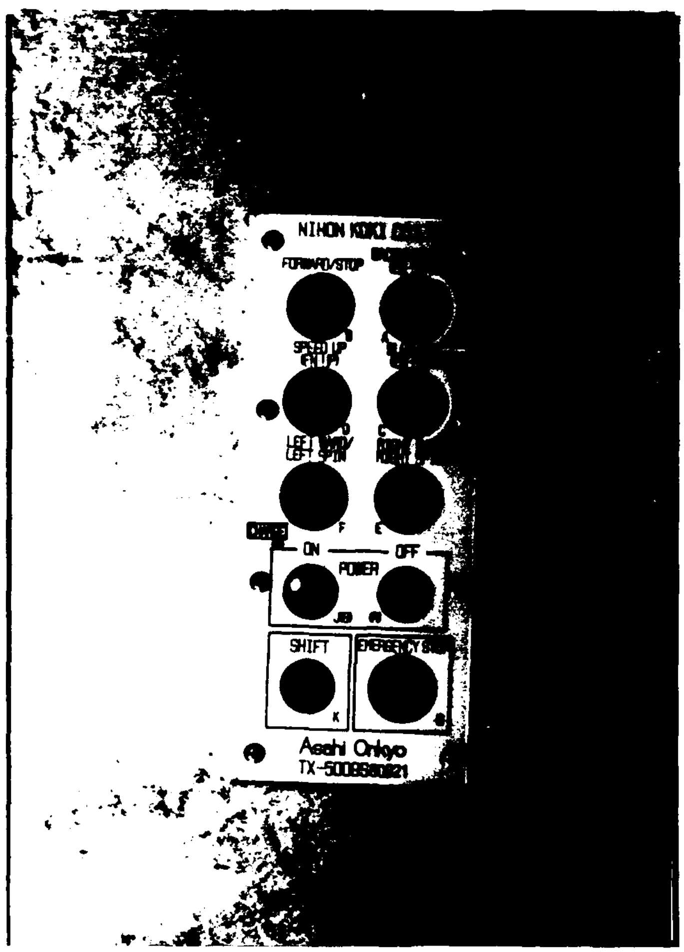


Figure 6.19 The Radio Transmitter

Figure 6.20 The Radio Receiver

The machine's mechanical systems: gasoline engine, gear boxes, and trowel blades, are comparable in durability to any of the U.S. manufactured ride-on power trowels. However, the electrically powered drive rollers are more sensitive to neglect and the elements than the mechanical systems found on ride-on trowels and overall, machine reliability is impacted the most by the environmentally sensitive control electronics utilized on the unit. In fact, the only break downs experienced during the test period occurred in the electronic control circuits.

A total of 17 units have been manufactured by the remote's developer. Those units have been used in 5 countries on 110 job sites to trowel over 5,000,000 SF of concrete flooring in warehouses and office buildings. The developer claimed that the unit used in this study was the only one to experience such an extent of break downs. Therefore, its performance should not be taken as representative of all such machines.

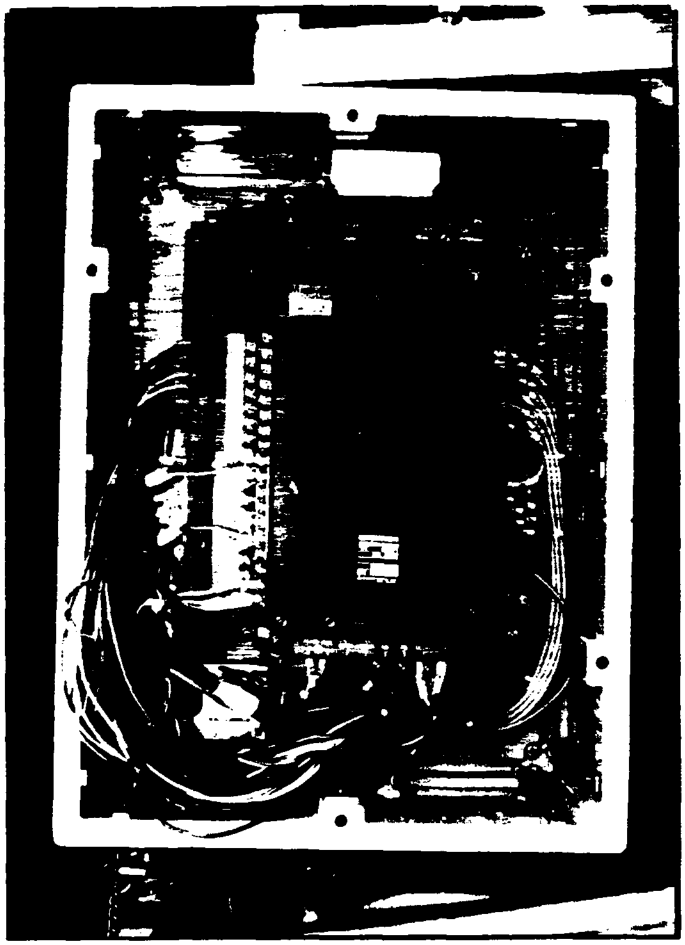


Figure 6.21 The Microprocessor

6.3.5 Maintainability

Required Clean Up and Storage - Clean-up after use is critical for the proper function of the remote controlled trowel's drive rollers on subsequent work. Proper clean-up is difficult due to the rollers' inaccessibility. Also, some machine parts are sensitive to moisture, so care must be taken when washing off cement residue and between uses the machine should be tightly covered.

Spares Availability - Since the machine is a prototype device, spares are not available in the United States at this time.

Technical Knowledge Required - Maintenance and repair of the remote controlled power trowel would require personnel in addition to those normally retained for maintenance of walk-behind and ride-on trowels. Beyond normal mechanics, technicians trained in the repair of electronic controls are required.

6.3.6 Portability

Required Transportation - Ideally, an inclosed truck with a 7-foot wide flatbed and overhead winch are required to transport the remote controlled trowel from site to site without exposing the electronics to adverse elements. In leu of an overhead winch, ramps and a loading winch can be utilized (See Figure 6.22), or at a minimum, an open flatbed and the outside support of a crane can be used. Field data collection revealed that one finishing contractor uses a goose-neck flatbed trailer with a chain-fall mounted on rollers which travels on an overhead track to lift ride-on trowels on and off slab, place them on his trailer, and transport them to new work sites.

On.Site Mobility - A crane is the best conveyance for the machine on site (See Figure 6.23), however, six men can lift it to move it a short distance and when it is on casters, it can be rolled around hard concrete by only one man. But, the installation and removal of the casters is cumbersome and involves floor jacks or other lifting devices.

Kajima learned some valuable lessons about mobility during their development of the Mark II automated trowel:[41] the machine must be light enough to be moved by 2-3 workers manually, its set-up and break-down must be simple, and there should be no requirement for specially trained personnel.

Overall, the remote controlled trowel has transportation and site mobility requirements similar to that of a ride-on trowel, but due to its sensitive electronics and design, it requires greater protection from the elements in transport and a crane for lifting.

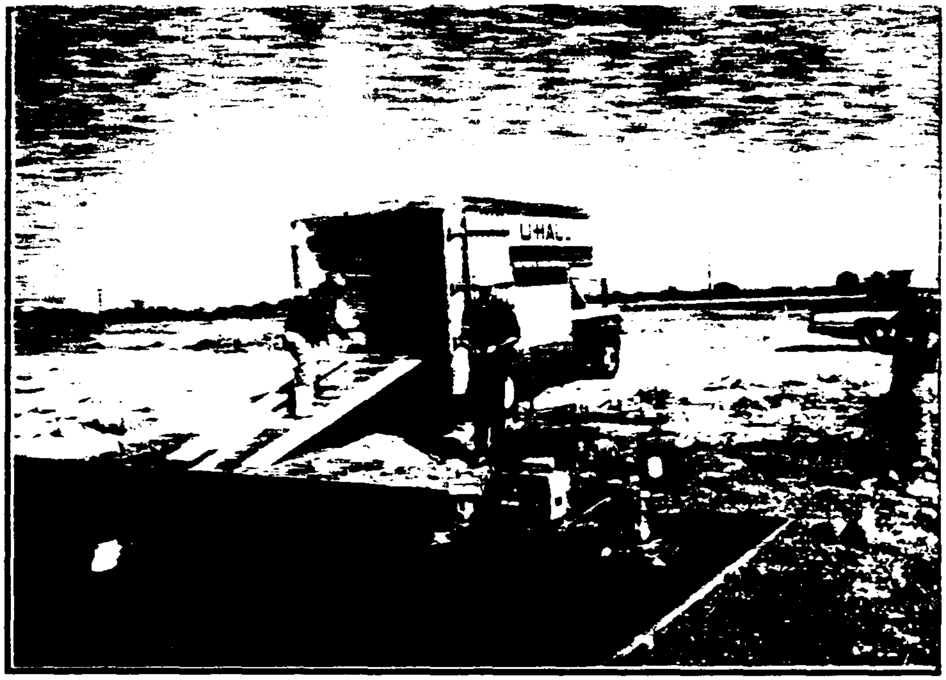


Figure 6.22 Transportation to Site

Figure 6.23 On-Site Mobility

6.4 Economic Performance

Section 4.1.3 sets the criteria which should be considered when judging the third major evaluation area, economic performance. Table 6.4 compares the costs and benefits of troweling by the various machines. A rate of 10% is used to annualize the acquisition cost. Each machine life is assumed to be five years, even though many walk-behinds are in service after ten years of use and the actual life of the remote trowel is unknown. Overhead includes the cost of support equipment, operator training, transportation, set-up and clean-up.

Since annual ownership, maintenance, and repair costs are taken as a percentage of initial acquisition cost, the high purchase price of the remote controlled trowel is the dominant factor in its high unit production cost. Since its initial cost is almost six times that of a ride-on trowel, it would have to have a production rate of close to six times that of the ride-on or possess an overwhelming benefit in the areas of quality or worker safety to justify its use. Since, its production rate is only roughly equal to that of a walk-behind trowel and it does not possess any overwhelming benefit in use, than the remote controlled trowel can not be economically justified over a ride-on or walk-behind trowel.

6.5 Human Interaction

How the human operator interfaces with the automated device is the subject of the fourth major area of evaluation. As detailed in Section 4.1.4, the worker's safety, comfort, and ability to be at one with the machine's controls must be assessed along with the appropriateness of the level of automation presented by the new device in the execution of its construction task.

Table 6.4 Economic Comparison of Power Trowel Equipment

		WALK-BEHIND	RIDE-ON	REMOTE CONTROLLED
PURCHASE COST	(PC)	$2,000.00	$7,000.00	$40,000.00
Life		5 yr	5 yr	5 yr
Annualized	(APC)=PC x (A/P,10,5)	527.60	1846.60	10,552.00
ANNUAL COSTS				
Tax, Ins, Int	18% of APC	94.97	332.39	1899.36
Overhead	10% of PC	200.00	700.00	4000.00
Average Maintenance and Repair	50% of PC averaged over lifetime	200.00	700.00	4000.00
Average Annual Costs	(AAC)	1022.57	3578.99	20,451.36
Average Daily Costs	AAC / 250 work days per year	4.09	14.32	81.81
DAILY OPERATING COSTS				
Fuel, Oil, Etc.	0.036xHP x$1.50x8 hr	2.60	9.94	2.60
Operator	$20.00/hr	160.00	160.00	160.00
Total Daily Cost	(TDC)	166.69	184.26	244.41
Daily Output	(DO)	3000 SF	15,000 SF	3000 SF
Cost per Square Foot	TDC / DO	5.6 ¢	1.2 ¢	8.1 ¢
BENEFITS		Most Flexible, Lightweight, Tighter Work Area, Floats & Finishes	Less Physically Demanding	Least Physically Demanding, Operator Not Subject to Vibrations

6.5.1 Controls Interface

Figures 6.24 and 6.25 respectively show the operation of the remote controlled trowel and its closest evaluation competitor, the ride-on trowel. The hand held transmitter of the remote controlled trowel allows the operator to stand as far as 100 feet away from the machine during its operation, while the ride-on operator is always directly on top of the troweling blades and the walk-behind operator is always directly behind them.

Observations of the ride-on and walk-behind trowels in use show that the operators look directly at the slab under the trowel blades 95% of the time and that they frequently adjust the trowel blade angle.of each trowel head to independently compensate for varying slab stiffness and to correct local slab defects such as humps or valleys. Operators also comment that they can "feel" the condition of the slab while riding the machine.

The trowel blade angle of attack on the remote controlled trowel must be pre-set before the machine is placed on the slab and cannot be adjusted during its operation. Also, as the operator allows space to come between him and the machine, his view of the interaction of the trowel blades with the concrete surface becomes limited. Finishers who have witnessed the operation of the automated trowels complain that this limited operator visibility is a major draw-back to their design, that the operator becomes less able to make proper decisions in the finishing of the slab as his information on the interaction of the trowel blades is limited through decreased field of view.

Figure 6.24 Remote Operation

Figure 6.25 Ride-On Operation

Since the automated trowels have no sensors which provide information on the slab stiffness, moisture content, local slab defects, and trowel blade interaction, the operators must have a good view of the trowel blades at all times. Thus, the remote controlled trowel operator must stand within 10 feet of the machine to effectively view his performance.

The actual control interface of the hand held remote is accomplished through the use of 10 push buttons which include 1 shift key, giving the unit 14 independent commands which control the machine. Directional control is accomplished through the sequenced issuance of 8 separate commands, while such functions as engine speed, start-up, and shut-down are controlled by the other 6 commands. In short, the hand held remote is a cumbersome device and lacks the simple ergonomics and user friendliness of even a household video game.

In all, the stick controls and seat-of-the-pants operational "feel" of the ride-on trowel provide the most natural interface between man and machine and allow for best work face viewing. The push button remote controlled trowel falls short in performance in these areas. Also, some suggest that the lack of practical sensor technology, which would enable automated control decisions based on the varying set-up times and surface conditions of a slab, means that troweling does not lend itself to automation at this time.[42]

6.5.2 Health & Safety

The remote control has as a benefit the elimination of the need for physical manipulation of mechanical controls on the machine itself, isolating the operator from its adverse effects. In contrast, the ride-on requires its operator to sit on top of the

machine and apply pressure to its controls, in the process being exposed to the machine's vibrations, noise, and exhaust fumes. The walk-behind also exposes the operator to these adverse effects through its control handle and in addition requires a fair amount of physical exertion in its use.

The separation of the operator from the machine also has its safety draw-backs. The further the operator stands from the machine's work-face, the more limited his field of sight, bringing the possibility of running the machine into unseen obstructions or depressions and causing a hazardous situation for others. The remote controlled trowel is equipped with a touch sensor around its perimeter which stops the machine if it bumps into a solid object, however, this sensor rests about 1 inch off the slab surface during operation, leaving the possibility of running over small imbedded objects or debris.

Overall, the benefits of removing the operator from the immediate proximity of the troweling machine are a slight safety and health advantage for the remote controlled trowel over the ride-on and a greater advantage for it over the walk-behind.

6.5.3 Required Skills

Hand trowelling is a skill learned fairly quickly through on-the-job training and perfected through years of practice. Anyone with normal motor skills and decent hand-eye coordination could become an acceptable hand finisher. Walk-behind trowels are usually operated only by experienced hand finishers because an understanding of the principles of troweling must first be possessed by the operator. Ride-ons are mostly

exclusively operated by only one or two of the most experienced finishers from the crew, usually the crew's working foremen, because seniority enables them to chose the less physically demanding ride-on over the walk-behind. Also, the company feels more comfortable entrusting the more expensive ride-on equipment with that individual.

Operation of the remote controlled trowel requires no special skills other than an understanding of troweling principals and experience with the multitude of conditions found in finishing work. Anyone experienced in hand troweling could operate the machine once they've mastered the confusing hand held controls.

6.5.4 Operator Comfort

Since the remote controlled operator must stand within 10 feet of the machine to properly view his work, there is minimal advantage in its use over ride-ons or walk-behinds in the aspects of noise, dirt, or task lighting. Furthermore, the remote controlled trowel offers no advantages which would enable task extension due to mitigation of weather, climate, or time of day effects.

As an advantage, the reduced physical demands and isolation from machine vibrations does enable persons not capable of manipulating a ride-on or walk-behind or unable to assume the kneeling position of hand troweling to operate the remote controlled power trowel.

6.5.5 Appropriateness of the Level of Automation

A major consideration when looking at the human interaction of the automated device is to judge the

appropriateness of the level of automation it brings to its discipline. Mainly, does the leveraging of the manpower required for this specific task fit with the overall allocation of personnel within the entire operation?

When manpower is saved in the finishing phase, this does not directly relate to reduced payroll. This is because finishing follows the more manpower intensive preparation and placement operations in the daily cycle of constructing concrete floors. Therefore, taking a man off the finishing operation only means he is free to help with the preparation work for the next day's pour. This will either compress the time required for preparation work or reduce the manpower requirements for the preparation phase. A better approach is to find the operation which is driving the overall crew size, make it more efficient, and level manpower requirements accordingly.

To get a feel for where automation could have the greatest impact on the construction of concrete floors, the allocation of labor across the placement and finish operations was examined. Standard productivity analysis tools were used to study the labor activities on four of the field testing sites.[43] As an example, lets look at information collected at the Sherwin-Williams warehouse site on October 17, 1989. The concrete floor for the 800,000 SF warehouse was placed in 50 foot wide lanes in a linear fashion. On this day, 27,500 sq ft were placed. Figure 6.27 represents graphically how the labor was employed for placement and finishing, while Table 6.5 shows a crew balance survey and Table 6.6 shows a work sample data sheet for that day's work.

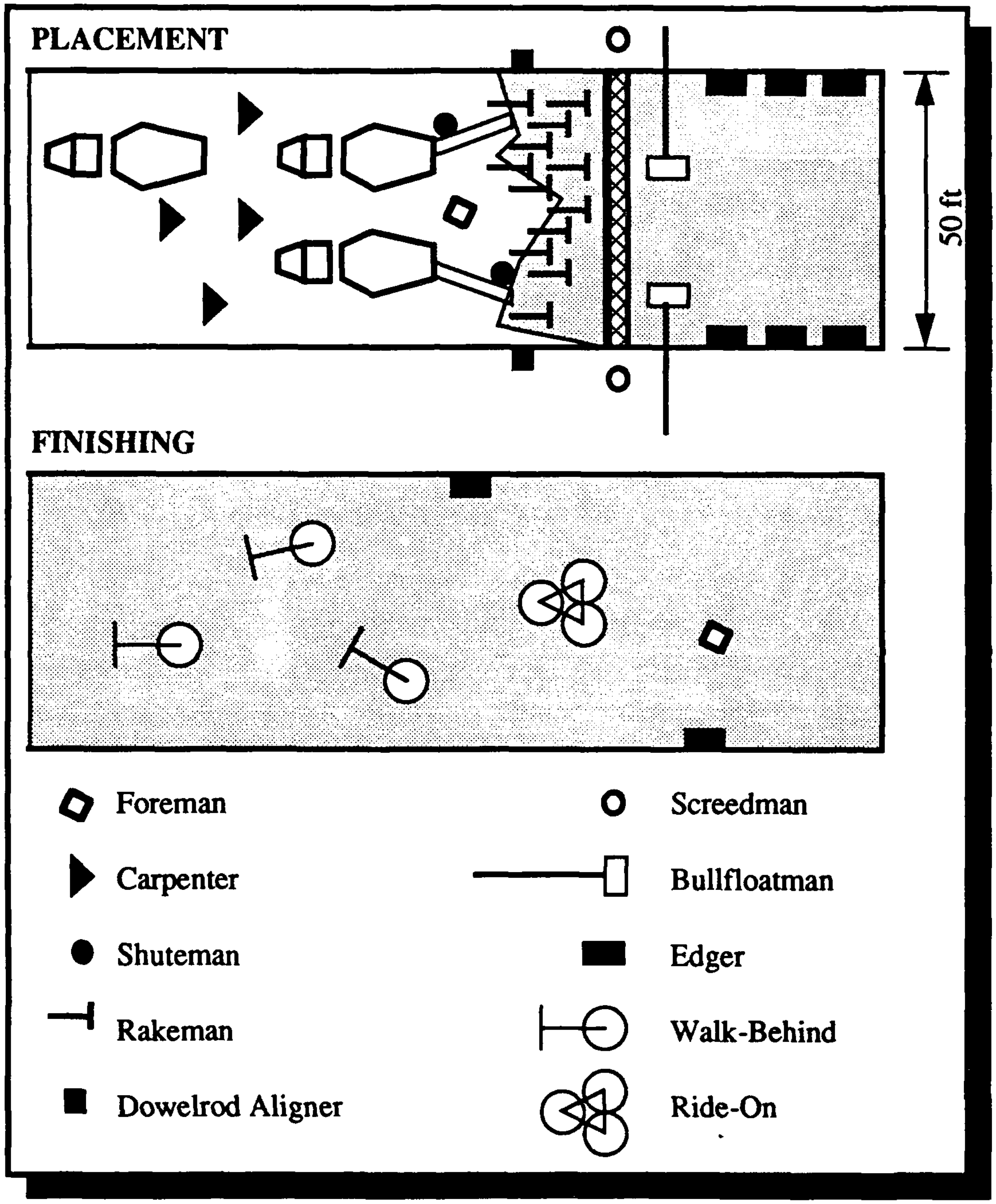


Figure 6.26 Linear Placement and Finishing Operations on Sherwin-Williams Site

Table 6.5 Crew Balance Survey for Sherwin-Williams Site

TIME	FOREMAN	CARPNTR	SHUTE	RAKE	SCREED	DOWELRD	BULLFLT	EDGERS	PLACE		EDGERS	WALKBND	RIDEON	OTHER	FINISH	REMARKS
7:00	1	3	2	12	2	2	2	4	28							Start Pour
7:15	1	3	2	12	2	2	2	4	28							
7:30	1	4	2	12	2	2	2	4	29							
7:45	1	4	2	12	2	2	2	4	29							
8:00	1	3	2	12	2	2	2	4	28							
8:15	1	3	2	12	2	2	2	4	28							
8:30	1	4	2	12	2	2	2	6	31							
8:45	1	4	2	12	2	2	2	6	31							
9:00	1	4	2	12	2	2	2	6	31							
9:15	1	4	2	12	2	2	2	6	31							
9:30	1	4	2	12	2	2	2	4	29		1	1		1	3	Float Starts
9:45	1	4	2	12	2	2	2	4	29		1	1		1	3	
10:00	1	4	2	12	2	2	2	4	29		2	2		1	5	
10:15											2	1		2	5	Stop Pour
10:30											2	2		2	6	
10:45											2	2	1	1	6	Ride-On Start
11:00											3	3	1		7	
11:15											3	2	1	1	7	
11:30											4	2	1		7	
11:45											2	3	1	1	7	
12:00											4	5	1	1	11	Excess Workers
12:15											7	4	1	1	13	Help Finsh
12:30											7	3		4	14	Gassing Ride-On
12:45											8	4	1	1	14	
13:00											8	4	1	1	14	
13:15											5	3	1	4	13	
13:30											4	3			7	Excess Workers
13:45											3	2	1		6	Leave
14:00												2	1	1	4	
14:15												2			2	
14:30												1		1	2	
14:45												1			1	
15:00												1			1	Complete
Placement M.H. = 95 Finishing M.H. = 40 [70%/30%]																

Table 6.6 Work Sample Data Sheet for Sherwin-Williams Site

JOB-SITE: Sherwin-Williams WEATHER: Windy, Cool (60°F) ACTIVITIES: Concrete Floor Pour			DATE: 10/17/89 TIME: 0800-1500 MAX CREW: 33
	DIRECT WORK	SUPPORT	DELAYS
Placement			
Observations	126	15	132
Percent of Total	46%	6%	48%
Finishing			
Observations	138	8	50
Percent of Total	70%	4%	26%

Analysis of the crew balance survey shows that placement was performed by an average crew size of 31 in 3.25 hours while floating and troweling took only an average of 7 men 5.75 hours, or 3.6 MH to place each KSF and 1.5 MH to finish each KSF. This indicates a 70% vs 30% manpower split for placement vs finishing. Table 6.7 summarizes data collected at the other field testing sites which supports the generalization that three times as much manpower goes into the placement operation as compared to the finishing operation in the construction of concrete floors.

Table 6.7 Placement vs. Finishing Manpower

SITE	DATE	PLACEMENT	FINISH
J.C. Penney Store	8/28/89	76.5%	23.5%
UT Sports Center	4/21/89	76.2%	23.8%
Fujitsu Warehouse	2/7/90	71.0%	29.0%
Sherwin-Williams Warehouse	10/17/89	70.4%	29.6%

Data collected at the J.C. Penney and UT Gymnasium sites further broke out manpower allocation within the finishing operation by examining the requirements for floating and troweling individually. Table 6.8 summarizes those results.

Table 6.8 Floating vs. Troweling Manpower

SITE	DATE	PLACE	FLOAT	TROWEL
J.C. Penney Store	8/28/89	76.5%	17.6%	5.9%
UT Sports Center	4/21/89	76.2%	9.5%	14.3%

Thus, troweling is only 10-20% of the manpower expended in the placement and finishing process. Also, Table 6.5 indicates that the finishing activities have a much higher effective work (a measure of activity efficiency) percentage [70%] than that for placement [46%].

These factors combine to suggest that automating placement operations can yield much higher pay-backs in work crew reduction then automating troweling at this time. This conclusion is supported by the fact that Fazio, Moselhi and Hason determined only a medium requirement for the automation of concrete finishing in their research,[44] while Kangari and Halpin determined a high need for automating concrete placement in their work.[45]

6.6 Business and Societal Interaction

The fifth and final major evaluation area examines how the automated device fits in with the corporate goals of the individual firm and how it is received by the surrounding

community. Section 4.1.5 fully details the evaluation issues for this area.

6.6.1 Social/ Cultural Acceptance

There existed an almost universal acceptance of the concept of employing the automated trowel in the construction of concrete floors. Owners, engineers, contractors, and equipment suppliers were all anxious to see "high tech" equipment brought to the construction site, while individual workers welcomed any device which made their work less physically taxing and more intellectually stimulating. Since concrete finishing is not dominated by unionized labor in Texas, areas with high union involvement may have different attitudes. However, little union resistance to the automation of concrete finishing operations is anticipated.

6.6.2 Market Pressures

The greatest market pressure in the U. S. is the economic bottom line. Increased competition in a smaller market has forced the acceptance of tighter profit margins and instills a reluctance by the U. S. construction industry to invest in risky new technologies.

In Japan, there is less emphasis on short term profits and accounting policies encourage investment in research and development. Their culture, and thus their ability to "woo" new clients, dictates a corporate image which involves the application of "high tech" solutions to today's "high tech" problems. Therefore, R&D is a significant part of any corporation's budget and why you'll find large technical staffs engaged in construction automation research at the largest Japanese general contracting firms.

These market pressures are also why there are four separate automated trowels under development within four separate Japanese contracting companies, while in the U. S., all power trowel development is undertaken by the relatively small equipment manufacturers and progress is limited by their available resources.

6.6.3 Labor Picture

The current automated trowels have the same labor requirements as walk-behind or ride-on trowels and do not significantly impact the sequencing of operations. Therefore, issues such as worker displacement and system integration have no bearing.

Presently, there is not a serious shortage of skilled concrete finishers in the U. S. However, predictions of future labor shortages for the entire construction work force should be heeded and development of methods which are less manpower intensive should be taking place in all areas of construction.

6.6.4 Machine Availability

The remote controlled power trowel is considered to be a prototype device and is not available for sale. Be that as it may, here is a thought for anyone considering the purchase of a new automated device: Consider the support which will be made available after the sale, will spare parts, technical support, and support equipment be available over the life of the machine?

6.6.5 Buyer's Characteristics

Ultimately, the individual firm must decide if automation fits into their operations today or if they should plan for it

tomorrow. Motivation for automating the operation: labor savings, increased quality, increased safety, or even corporate image, must be weighed against business volume, cash reserves, research posture, and attitudes toward risk when making that decision. Although the remote controlled trowel is not ready for salc today, when it is, it will bring no unique factors to this final equation.

CHAPTER 7

EVALUATION OF TEST RESULTS

7.1 Overall Effectiveness of the Remote Controlled Power Trowel

The previous chapter chronicles the events of and details the information gathered during the actual testing of the remote controlled power trowel. Here, the results of that testing are examined and the machine's advantages and disadvantages within the five major evaluation areas are discused.

7.1.1 Project Environment

Task Analysis - The physical environment for concrete finishing in the U. S. is congested and dirty, making the mechanically simpler walk-behinds and ride-ons better suited than the sophisticated electronics of the remote controlled trowel.

It would be difficult for the typically small U.S. concrete finishing firm to absorb the capitol expense associated with purchasing an automated trowel.

The work of finishing concrete itself is highly variable and is not fully adaptable to automatic control.

All methods require the same number of operators, making the device with the highest production rate the most manpower efficient. Figure 7.1 shows us that the ride-on power trowel is the most efficient method of troweling large areas of concrete flooring.

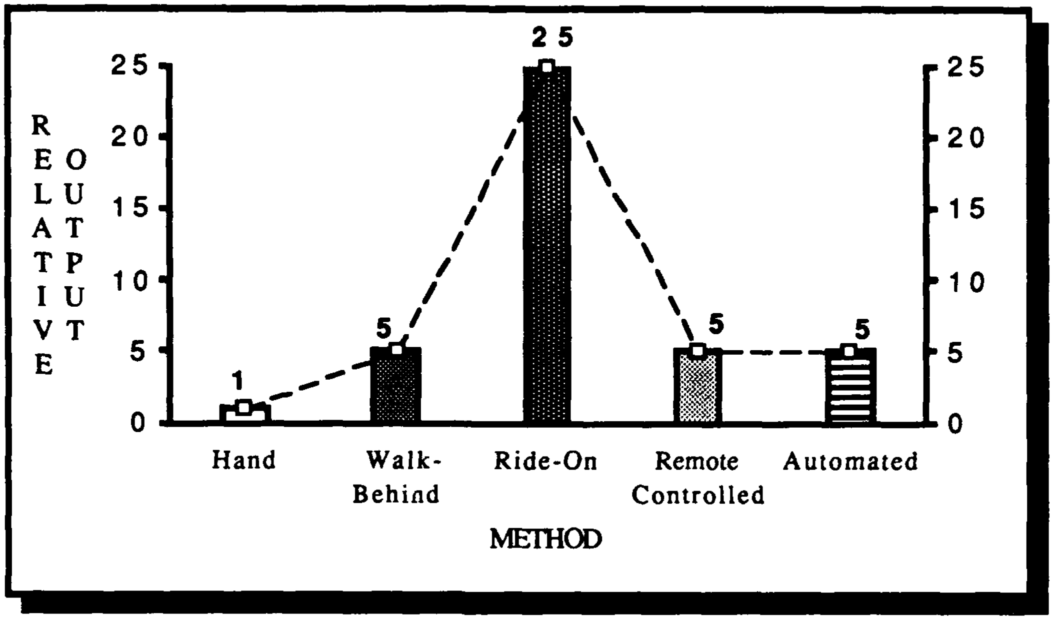


Figure 7.1 Productivity vs. Degree of Automation

Automation of troweling does not increase the work envelope thru the minimization of the effects of weather or climate.

Impact on Project Management - Automation of troweling operations presents no appreciable impact.

Impact on Design & Procurement - Automation of troweling operations presents no appreciable impact.

Impact of Possible Failure - Automation of troweling operations presents no appreciable impact.

Therefore, the remote controlled power trowel is not as well suited to interact with the project environment of the U. S. construction industry as are the mechanically simpler ride-on and walk-behind power trowels.

7.1.2 System Performance

Production Rate - The remote controlled power trowel is roughly equal to a walk-behind power trowel in average production out-put. The ride-on power trowel can finish five times as much floor surface area in the same amount of time.

Quality - The remote controlled trowel produces a surface hardness equal to the ride-on, but this level of hardness is insignificant when compared to the level achievable with the use of dry shake hardeners. The flatness and levelness of the slab are not significantly effected by the choice of troweling machine.

Operability - The remote controlled trowel has a slightly more restricted work envelope than that of the ride-on trowel. The smaller size and weight of the walk-behind trowel gives it the greatest work envelope.

Reliability and Durability - The remote's electronics make it more susceptible to breakdown and make it more difficult to repair.

Maintainability - Additional maintenance skills are required for the automated trowels over conventional methods.

Portability - The remote trowel is equal in mobility to a ride-on, but requires more care in transport to protect it from the elements.

Therefore, the remote controlled trowel's physical systems are not developed to the extent required for its widespread use and offer no significant benefits over other troweling methods.

7.1.3 Economic Performance

Ride-on and walk-behind power trowels perform at lower unit costs than the remote controlled trowel. Figure 7.1 showed us that the remote and walk-behinds are equal in production, while the ride-on's production is five times these two. Combine these rates with costs and Figure 7.2 shows that the ride-on can finish concrete floors at a square foot cost of 1.2 ¢, while the walk-behind's cost is 5.6 ¢ and the remote's cost is 8.1 ¢.

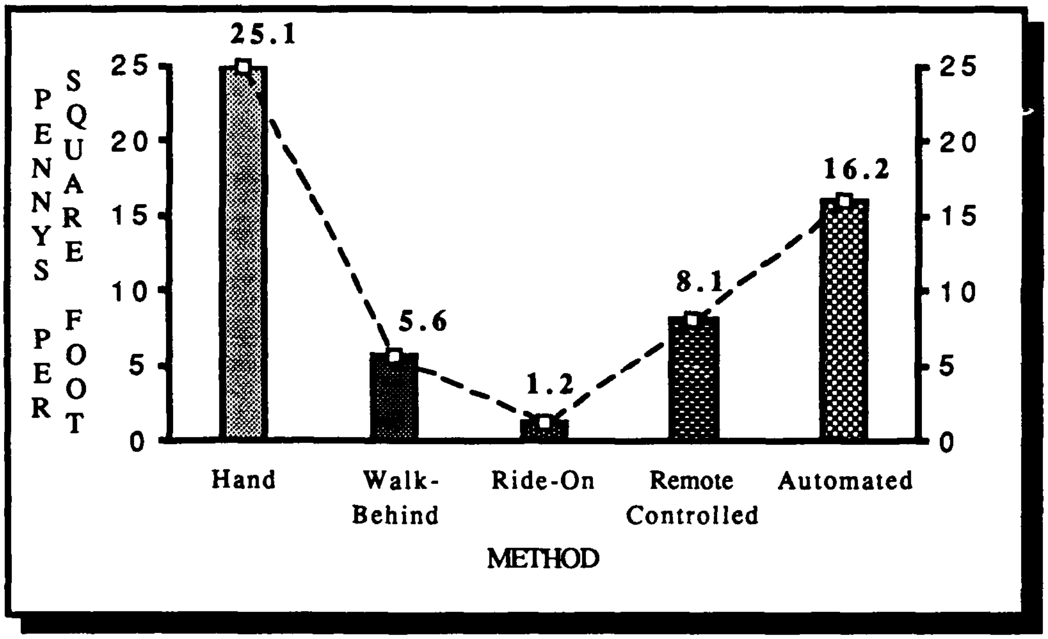


Figure 7.2 Cost vs. Degree of Automation

Therefore, since the remote controlled trowel's benefits do not out-weigh cost considerations, its use is not economically supported.

7.1.4 Human Interaction

Controls Interface - The ride-on power trowel provides the best controls interface for the power troweling operator.

Safety & Health - The remote controlled trowel has a slight advantage over ride-ons and a greater advantage over walk-behinds in isolating the operator from adverse health conditions.

Required Skills - No special requirement for the operators of automated trowels.

Operator Comfort - The remote would enable a greater spectrum of worker profiles to trowel concrete due to its reduced physical demands.

The remote controlled trowel offers many advantages for human interaction in the areas of comfort and safety, but its present control interface impedes production. Therefore, it represents a promising technology for future development.

7.1.5 Business and Societal Interaction

Acceptance - An almost universal acceptance of the concept of automated construction devices was found, with a willingness to see these mentally stimulating devices and their potential for reduction in physical labor brought to the construction site.

Market Pressures - The short-term profits emphasis of United States industry limits its abilities to make research breakthroughs. Keep in mind, that even though the ride-ons out performed the automated trowels, that they are a mature technology while the automated trowels are an infant one.

However, eventually the automated technology will mature and labor may become short of supply, making the Japanese the best positioned to take a commanding lead in this area of construction.

Labor - Future predicted shortages will dictate the use of automated devices throughout the construction process.

Availability - Since the remote controlled trowel is a prototype machine, it is currently unavailable for purchase.

Company Image - Automation research can boost a company's image with clients and be an aid to new business generation.

Therefore, business and societal factors indicate that investing in automation research today can bring valuable returns in the very near future.

7.2 Appropriate Level of Automation in Concrete Finishing Today

Even if the total troweling cost per square foot of the remote controlled trowel can be reduced to that of a ride-on, there is no leveraging of manpower presented by this method of operation. Therefore, the ride-on trowel represents an appropriate level of automation for concrete floor troweling today.

However, analyzing the entire process of constructing concrete floors shows that the best route to reducing labor costs today is thru increasing the level of automation of placement operations first. Since placement and not finishing should be the focus of automation implementation at this time, one should look

at what devices are available to leverage placement manpower but are not fully utilized.

Vibrating, roller, and laser screeds are produced by several manufacturers, but are seldom used. They can replace the vibrating and strike-off operations and can facilitate wider pours, reducing crew size and giving more uniform results in a faster time. Also, properly planning pours allows for long strip construction versus a checkerboard pattern, reducing forming by half and allowing highly efficient linear production techniques.

The choice for today would be to integrate the ride-on power trowel more fully into finishing operations and to optimize the use of existing labor leveraging devices, such as vibratory screeds, for concrete placement.

7.3 Potential for Automation in Concrete Floor Construction Tomorrow

Keeping an eye to the future, there is much to indicate an inevitable shift in paradigms. Ten years from now, the only contractors left in the finishing business may be those with fully autonomous finishing machines. In fact, several Japanese construction firms have as their goal the development of fully automated construction systems. One firm, Ohbayashi Corporation, announced in September 1989 that they have already developed such a fully automatic system for buildings. It is based on pre-casting all building components then utilizing automated warehousing, materials handling and assembly equipment to complete the construction.[46]

With this in mind, the remote controlled power trowel becomes a very valuable asset to its developer, allowing the

construction company to gain precious experience with the development and use of an automated construction device.

7.4 Appropriateness of the Standard OT&E Plan to this Evaluation

The Standard Operational Test and Evaluation Plan was designed to guide the development of operational test and evaluation programs for specific automated devices. It sets forth a procedure for identifying critical testing issues, developing the specific test program, collecting the data, and analyzing & reporting the results. This format enabled us to logically approach the evaluation of the remote controlled power trowel and helped us to attain all of the test objectives. The plan is therefore judged to be fully appropriate to the investigation of automated construction devices.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Review of this Study

Almost as much human intervention of the productive process is required in the construction industry today as there was four decades ago, while at the same time, other industries have significantly reduced the negative effects of their human intervention by embracing automation.

At present, there are more than 60 automated devices under development for the construction job site and we are poised on the verge of an automation revolution. To cope with the myriad of production options offered by the new machines being introduced almost daily, the construction industry requires a standard evaluation plan which will enable systematic examination of these options and aid in the exchange of lessons learned.

After reviewing work presently underway inside and outside of the construction community and gaining a clear grasp of what is involved in testing, the first half of this study is completed by the presentation of the Standard Operational Test and Evaluation (OT&E) Plan for automated construction devices.

The second half of this study concerned itself with the actual testing of a particular automated device, the remote controlled power trowel. Power troweling was found to be performed after the floating of freshly poured concrete floors to

produce a smooth, hard, dense surface and is typically used on warehouse and office building floors. Also, this study found that equipment available in the United States today for troweling is: hand trowels, walk-behind trowels, and ride-on trowels. The automated trowels must be able to out perform these methods in order to be introduced successfully onto the U.S. construction site.

Testing matched the remote controlled trowel against these other methods and judged its performance in the areas of: project environment interaction, system performance, economic performance, human interaction, and business & societal interaction. In performing the OT&E, all of the test objectives were met: 1.) to evaluate the overall performance of the remote controlled power trowel, 2.) to determine the appropriate level af automation for finishing work today, 3.) to determine the potential for automation in concrete floor construction tomorrow, and 4.) to judge the appropriateness of the Standard OT&E Plan to this evaluation.

Here, the study is completed with a summary of the test results, some suggestions for improving the performance of automated trowels, and final thoughts about automation and the construction industry.

8.2 Use of the Remote Controlled Power Trowel

The remote controlled trowel was compared with the walk-behind and ride-on trowels in the five major evaluation areas first presented in Chapter 4. A summation of the findings presented in Chapter 7 is shown in Table 8.1. A plus sign represents that the machine offers a benefit in that area, a

minus sign means that it is a limitation in that area, and an equals sign means that it is neither.

Table 8.1 Comparison of Walk-Behind, Ride-On, and the Remote Controlled Power Trowels

	Walk-Behind	Ride-on	Remote Controlled
PROJECT ENVIRONMENT			
Task Analysis	+	+	-
Impact on Project Mgmt	=	=	=
Impact on Design & Procurement	=	=	=
Impact of Failure	=	=	=
SYSTEM PERFORMANCE			
Production Rate	=	+	-
Quality	=	=	=
Operabiiity	+	+	-
Reliability/ Durability	+	=	-
Maintainability	+	=	-
Portability	+	-	-
ECONOMIC PERFORMANCE			
Unit Production Cost	=	+	-
Benefits	=	=	=
HUMAN INTERACTION			
Controls Interface	=	+	-
Safety & Health	-	=	+
Required Skills	=	=	=
Operator Comfort	-	=	+
BUSINESS/ SOCIETAL INTERACTION			
Acceptance	=	=	=
Market Pressures	=	+	-
Labor Availability	=	=	=
Machine Availability	+	+	-
Company Image	=	=	+

\+ Bebefit - Limitation = Neither

The benefits and limitations of the remote controlled power trowel, as represented in Table 8.1, were found to be as follows:

Benefits -

- Isolates Operator from Adverse Health Conditions
- Enables Expanded Worker Profile
- Valuable Experience Tool for Learning Automation
- Platform for Future Full Automation of Finishing
- Excellent Public Relations Tool

Limitations -

- Environmentally Sensitive Electronics
- Disproportional Capitol Cost
- Requires Full Time Operator
- Production Only Equal to Walk-Behind Trowel
- Push Button Controller is a Difficult Interface

The limitations, particularly the unit production cost, outweight the benefits of the machine's use at this time. In its present state, the remote controlled power trowel is not recommended for use on U. S. construction sites. However, it is recommend that the ride-on power trowel and labor leveraging placement devices be more fully integrated into the work.

However, it must be remembered that the development of modern ride-ons and automated trowels started at the same time and that these were two solutions to the same problem One, the modern ride-on, was the maturization of an existing technology, while the other, the automated trowels, was the birth of a new one. Consequently, the mature mechanized technology is presently more efficient than the infant automated

technology, but this does not mean that the infant technology will someday mature to become the most desirable system.

8.3 Technology Needs to Advance Automated Trowels

Tim Killen, in his address to the 6th ISARC, noted that today's prototype automated construction devices must undergo several technological advances to become fully feasible. Those advancement areas were mobility, sensor, effector, & control technology, operator training, and weight reduction.[47]

The automated power trowels currently under development must also make advances in these areas, namely:

Mobility - Reduction in weight and ability to self propel onto and off of the concrete slab.

Sensors - An ability to mechanically perceive the same information that a human finisher utilizes in making troweling decisions is required to fully automate finishing work. The sensors which need to be integrated with the machine controls must detect: moisture, stiffness, voids, levelness, and flatness

Effectors - To expand the capabilities of the automated trowels and bring them more in line with present mechanical devices, they must have their trowel blades be able to be fitted with float shoes, they must be able to have the blade pitch changed during operation, and their production rates must be comparable to ride-on trowels.

Controls - The controls of the automated devices must offer a natural link between the operator and the work performed to enable the machine to be most effective in carrying out its task.

Operator Training - The final required technological advance is the key to successful implementation of automation, successful operator training. Training involves[48]: 1.) making everyone on the site aware of the general capabilities and uses of the automated device, 2.) detailed training of the device's operators, and 3.) training of maintenance personnel, especially in electronics repair. Training can overcome worker resistance, organized labor is generally more receptive to automation when it knows that automation can bring cleaner jobs, enhanced safety, job excitement, and be valuable in recruiting "white-collar" workers into the construction industry.

8.4 Lessons Learned for Automation

Tasks requiring judgement and skill are more difficult to automate than those which do not. On the surface, it appeared to the Japanese that troweling concrete floors was simply monotonous and repetitive and they choose to start their automation research with such a simple task. What they overlooked here was all the information the finisher actually uses to skillfully accomplish his work. Furthermore, they based their technology advancement on the replacement of hand finishers, not on the replacement of ride-on trowel operators. Conversely, by studying the entire floor construction cycle, they may have been led to the conclusion that automating placement operations first would bring the greatest labor savings.

The very human temptation here is to "leap" into a research project and "do something", even if its wrong. Like any other major corporate decision, automation development must be approached with a great deal of planning - isolate a suitable application, identify your research objectives, consider all of the

drawbacks, fully document current methods of operation, and examine the technical feasibility before jumping into development.

The most valuable lesson learned from studying the remote controlled power trowel is- before investing in automation research, make the best of your efforts by attacking those tasks which offer the greatest payback potential for your chosen objectives and fully investigate available technology, starting research with the most advanced form as your departure baseline.

8.5 Motivations for Implementing Automation Revisited

In Section 1.3, fifteen motivators for performing automation research were presented. Those motivators are based on cost savings (Increased Productivity, Reduced Labor and Material Costs), schedule compression (Reducing Lead Times, Reduced Labor Shortages, Better Worker Utilization, Reduced Jurisdictional Disputes), task extension (Hazardous Environment Mitigation, Improved Quality), worker safety and health (Improved Safety, Improved Environment), and industry advancement (Improved Quality, Motivating the Individual).

Ideally, these motivators should all be satisfied in the development of an automated device, but any one is justification enough for an involved research effort. For example, the Japanese may not have produced automated trowels which save money or time, but the machines certainly improve worker health and advance the state of the industry. What then are the roles and possible motivators for the various parties in the construction industry to be involved in the advancement of automation?

Researcher - Why should I develop?
- General Industry Advancement

Equipment Manufacturer - Why should I produce?
- Open New Markets

Specialty Contractor - Why should I buy?
- Competitive Edge
- Schedule and Cost Enhancement
- Task Extension
- Worker Safety Enhancement

General Contractor - Why should I sponsor?
- Marketing Tool

General Industry Advancement
- Schedule and Cost Enhancement
- Task Extension
- Worker Safety Enhancement

Owner - Why should I sponsor?
- Marketing Tool
- General Industry Advancement
- Guarantee of End Product Quality
- Worker Safety Enhancement
- Schedule and Cost Enhancement

Labor Union - Why should we encourage?
- Job Security through Competitive Edge
- Recruiting Tool
- Worker Safety Enhancement

Government - Why should we support?
- Competitive Edge for Domestic Industry
- General Industry Advancement
- Worker Safety Enhancement

The point here is that everyone connected with the construction industry has a reason to be involved in the advancement of automation technology and that that advancement will take everyone's involvement. If the U.S. construction market chooses to remain competitive in the next century, it is time to stop postulating on the merits of automating construction and to just start doing it.

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VITA

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